

**ACTIVATION CROSS-SECTION MEASUREMENTS
AND
GIANT-RESONANCE STUDIES
USING NEUTRON CAPTURE**

Rogério Zorro

Lund 1986

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Title and subtitle ACTIVATION CROSS-SECTION MEASUREMENTS AND GIANT-RESONANCE STUDIES USING NEUTRON CAPTURE		
Abstract <u>(n,γ) Activation measurements</u> Activation measurements of (n,γ) cross sections for non-magic nuclei are difficult in the MeV region, owing to the influence of low-energy background neutrons. Methods were developed to minimize the influence of this background and to correct for the remaining contributions. The methods were applied to measurements of the (n,γ) cross sections in ¹¹⁵ In and ¹⁹⁷ Au in the energy region 2.0-7.7 MeV. The results show that old measurements, in which only partial corrections were made for background neutrons, are in error <u>Giant resonance studies</u> Studies of the isovector giant quadrupole resonance (IVGQR) in nuclei are possible using radiative neutron capture. Here the IVGQR is observed in the fore-aft asymmetry of the γ-ray angular distributions around 90° with respect to the beam. The asymmetry is attributed to the effect of interference between γ rays from the isovector E2 state and E1 radiation. The IVGQR's in ⁴¹ Ca and ⁹⁰ Y were studied in the fore-aft asymmetries of γ ray angular distributions from the ⁴⁰ Ca(n,γ ₀), ⁴¹ Ca and ⁸⁹ Y(n,γ) ⁹⁰ Y reactions. The asymmetry results, interpreted in the framework of the direct-semidirect (DSD) model, show that the T _{<} component of the IVGQR in ⁴¹ Ca is located at an excitation energy of 32.5 ±1.5 MeV, has a width of 5 MeV and exhausts the fraction of the energy-weighted sum rule (EWSR) available for the T _{<} component. For ⁹⁰ Y, the resonance is located at 26 ±1 MeV, has a width of 10 ±2 MeV and also exhausts the portion of EWSR available for the T _{<} component.		
Key words ¹⁹⁷ Au(n,γ), ¹¹⁵ In(n,γ) E=2-7.7 MeV, measured σ(E). Compound-nucleus analysis ⁴⁰ Ca(n,γ ₀), ⁸⁹ Y(n,γ), ²⁰⁸ Pb(n,γ), Giant-resonance studies, DSD calculations		
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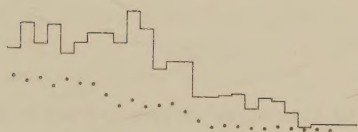
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Rogério Zorro

Date

April 9, 1986



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Foreword

This booklet is a doctoral thesis in nuclear physics which will be publicly defended on May, 23 1986. The type of thesis presented here is a "sammanläggningsavhandling" which consists of several separate papers and a summary of the work, in contrast to a monography. In the present case the thesis consists of five papers, of which four have been published previously in the international journals "Nuclear Instruments and Methods" and "Nuclear Physics", and one (paper V) is a Lund University report which will be submitted for publication.

The work, carried out partly at the University of Lund and partly at the Tandem Laboratory in Uppsala, consists of experimental studies of neutron-capture reactions in the MeV region.

The realisation of the experiments could hardly have been possible without the joint efforts of the scientific, technical and administrative staff at the two accelerator laboratories. In addition to those who have guided me in this work and participated in the experiments (the complete groups of collaborators are listed in each paper) others have contributed in their own ways.

To all I wish to express my gratitude:

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I worked more closely, Per Andersson, Stefan Crona, Ane Håkansson, Andrej Likar, Anund Lindholm and Nils Olsson for their many illuminating remarks and inspiring discussions about physics and life in general and for providing an easy and friendly social atmosphere during the course of this work; The members of the accelerator staffs, Christer Nilsson, Kjell Håkansson, Gösta Widman and Inge Karlsson who have not spared any effort in producing fine ion beams from the (often) capricious accelerators; The members of the mechanical and electronics workshops whose professional pride has been of great importance for the experiments; Elna-Greta Broomé who, through her skilful drawings, has helped to convey the information contained in the papers; Helen Sheppard who has striven to translate my less than perfect *english* into correct English.

Finally, my thanks go to Elisabeth for her encouragement and understanding, my gratitude is difficult to express in words.

Lund, April 1986

Roger Hägg

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INTRODUCTION

Studies of the atomic nucleus are possible only through the alteration of the energy or momentum states or both at the same time. Natural radioactivity was the only means available for nuclear physics studies in the early days of the discipline (see for example ref. [Ch32]). Most of present-day experiments, however, consist of bombarding the nucleus with charged or uncharged particles. Charged particles (electrons, protons, α particles, etc.) are produced directly and given the necessary kinetic energy in accelerators while uncharged particles are produced indirectly with the aid of accelerators. To the latter group belong high-energy γ rays (created, for example, when electrons are slowed down in matter) and monoenergetic neutrons which, in the MeV region, are usually obtained from reactions between the hydrogen isotopes. The results of the bombardment, i.e. the reaction products which emerge in the form of electromagnetic or particle radiation, are detected, registered and interpreted.

The detectors may be photographic emulsions, Geiger-Müller counters, semi-conductor or scintillation detectors, etc. In all these devices the radiation is detected in that it deposits its kinetic energy by directly or indirectly ionizing and exciting the atoms in the detection medium. The passage of radiation through a photographic emulsion can be made visible, after developing, as tracks. In the other types an electric signal is generated, amplified and further processed to be registered in a computer.

As to the interpretation of the results there does not yet exist in nuclear physics a unified theory to predict and explain the outcome of all experiments. This situation is in contrast to that in other branches of modern physics, e.g. atomic physics, where the interactions are due to the electromagnetic force alone. The phenomena, no matter how complex, can be predicted by the theories of quantum mechanics (quantum electrodynamics) and relativity although computational difficulties most often impose simplifications on the theoretical treatment. In nuclear physics too quantum mechanics and relativity are applied to explain the experimental results. In addition to the common computational barriers the same knowledge does not, however, exist of the detailed interactions between the constituents of the nucleus on a microscopic level. The results of experiments have to be interpreted with the aid of plausible idealizations and simplifications of the mechanisms subjacent to them. These idealizations and simplifications are called "models". The nucleus is neither a liquid drop nor a spring nor a rugby ball. Nevertheless, such ideas, taken from the macroscopic world, have been successfully applied to explain certain aspects of nuclear behaviour.

A model which is successful when applied to a certain nucleus or nuclear reaction may fail when applied to other nuclei or to the same reaction but in another energy region. It has been the aim of the present works to provide experimental results, as accurate as possible, with which the predictions of theoretical models can be compared.

One of the simplest types of nuclear reactions is the capture of a neutron by a target nucleus. In the capture process the excess energy is radiated away in the form of one or several γ rays and a new isotope of the target is formed. Compared with charged particles the neutrons have the advantage of not being affected by the nuclear Coulomb barrier. The interaction between the incoming neutron and the nucleus is due to the nuclear force alone. Neutrons in the $^{89}\text{Y}(n,\gamma)^{90}\text{Y}$ reaction or protons in the $^{89}\text{Sr}(p,\gamma)^{90}\text{Y}$ reaction may, for example, be used to reach a specific final state in ^{90}Y . The information which can be obtained is the same in both cases. However, while neutrons can be used at all energies and applied to all mass numbers, the penetration of protons into the nuclear interior is hindered by the repulsive Coulomb potential. This is low for the lightest nuclei, about 3 MeV in ^{12}C , but rises to about 16 MeV for the heaviest.

Low yields and difficulties in shielding are the main disadvantages when using monoenergetic neutrons in the MeV region. The consequences are, in the first case, that a relatively long time is needed to collect the data and, in the second, that special experimental set-ups and techniques must be used. The difficulties increase substantially with increasing energy. The majority of neutron-capture experiments have been performed in the eV and keV regions. However, the developments during the last fifteen years have shown that radiative neutron-capture studies are possible also in the MeV region.

Neutron-capture studies may be performed using two different methods - the activation and the spectrum methods. Using the activation method only the total capture cross sections can be measured. The spectrum method may be used in measurements of the partial cross sections, the excitation functions or the angular distributions of γ rays leading to bound states in the final nucleus. Both methods have been applied in the present work.

This thesis is based on the following papers:

- I THE INFLUENCE OF BACKGROUND NEUTRONS ON (n, γ) ACTIVATION MEASUREMENTS IN THE NEUTRON ENERGY REGION 2.0-7.7 MeV.
Nucl. Inst. and Meth. A234(1985)573
- II CROSS SECTIONS FOR $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$ AND $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$ IN THE NEUTRON ENERGY REGION 2.0-7.7 MeV.
Nucl. Phys. A443(1985)404
- III STUDY OF THE $^{208}\text{Pb}(n, \gamma)^{209}\text{Pb}$ REACTION BETWEEN 0.8 AND 7.7 MeV.
Nucl. Phys. A382(1982)71
- IV THE GIANT ISOVECTOR E2 RESONANCE IN CALCIUM OBSERVED IN RADIATIVE NEUTRON CAPTURE.
Nucl. Phys. A419(1984)509

V A STUDY OF THE ISOVECTOR E2 RESONANCE IN YTTRIUM

Nuclear Physics Report LUNFD6/(NFFR-3056)/1-29/(1986)

Papers I and II report on experiments performed with the 3 MV tandem Van de Graaff accelerator at the Pelletron Laboratory in Lund. This work was performed to find methods for accurate (n, γ) activation cross-section measurements. The methods were applied to measurements of the cross-sections in ^{115}In and ^{197}Au .

Papers III - V report on experiments performed with the 6 MV tandem Van de Graaff accelerator at the Tandem Accelerator Laboratory in Uppsala (TLU). Measurements of excitation functions and angular distributions were undertaken to study the giant dipole states in ^{209}Pb and ^{41}Ca and the isovector giant quadrupole states in ^{41}Ca and ^{90}Y .

1. ACTIVATION MEASUREMENTS

In the process of radiative capture of a neutron with kinetic energy E_n in a target nucleus, a new isotope of the target is formed and the excess energy, i.e. the kinetic energy of the neutron plus its binding energy, E_b , is carried away by one or several γ rays. It takes a time of the order of 10^{-22} to 10^{-16} seconds for the residual nucleus to reach the ground state or some meta-stable state.

In measurements of the total capture cross section one may use the spectrum method or, if the residual nucleus is radioactive with a suitable half-life, the activation

method. In the spectrum method the prompt γ rays are detected and the spectrum integrated to give the total capture cross section. In the activation method, as the name suggests, a sample is first irradiated for a certain time. After irradiation it is moved to a detector where its activity is measured.

Both methods are easy in principle but difficult in practice owing to the effects of background neutrons. This is illustrated schematically in fig. 1 for the ^{197}Au nucleus.

In the spectrum method only γ rays from transitions between the capturing state and bound states in ^{198}Au are with certainty due to capture. The pulse heights corresponding to energies less than E_n may be due to γ rays from transitions through unbound states and partial energy deposition in the detector. However, these may also be due to γ rays following inelastic scattering and must therefore be discriminated.

In the activation method it is impossible to distinguish between capture of source neutrons and capture of background neutrons. These have, on the average, a considerably lower energy. For non-spherical nuclei, which may have huge capture cross sections for low-energy neutrons, the situation is particularly troublesome. From the curve in fig. 1, where the cross section is plotted versus neutron energy, one can deduce that the presence of a minute low-energy neutron flux completely spoils the measurements.

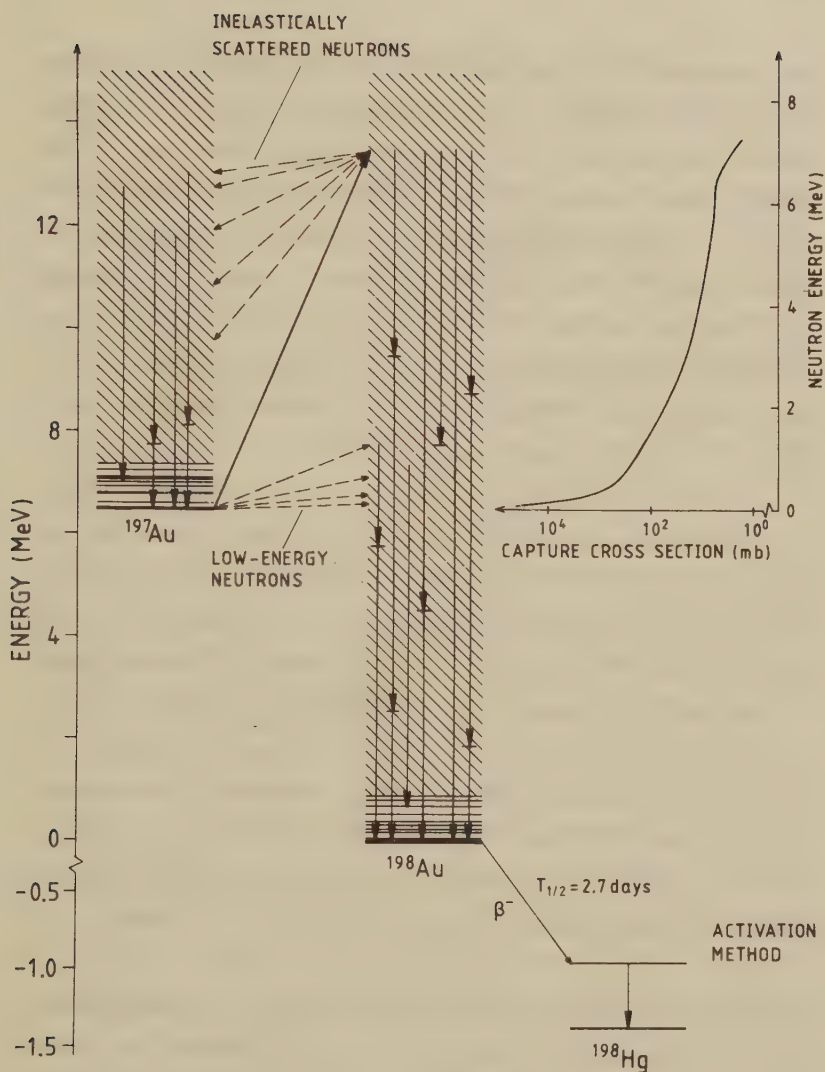


Fig. 1- Schematic representation of neutron capture in ^{197}Au . The source neutrons are represented by the heavy arrow. The γ rays from transitions between levels in ^{198}Au are detected in the spectrum method while in the activation method either β^- or the γ rays from transitions in ^{198}Hg are detected.

The possibility of systematic errors - caused by low-energy neutron contamination - in measurements of (n,γ) activation cross sections for MeV neutrons was pointed out in 1949 [Hu49]. These systematic errors were partially taken into account in early measurements of capture cross sections at several neutron energies [Jo59], [Me67] (see also [An85] where a review is given of this subject). However, the influence of low-energy neutrons on capture cross-section measurements was first accorded closer attention when comparison between measurements performed with the activation method and the more recent spectrum method became possible. The majority of the measurements were performed at $E_n = 14$ MeV for nuclei in the whole mass range. While the cross sections obtained with the spectrum method at this energy showed a constant value (around 1 mb) for mass numbers above 60 [Cv69], [Cv70], [Dr71] those obtained with the activation method displayed shell-structure effects. For nuclei with closed neutron shells there was agreement between the two methods whereas the activation results departed, sometimes more than a factor of ten, for nuclei with non-closed neutron shells.

Apart from the explanation that the activation measurements were marred by systematic errors [Dr71], [Ha70] it was suggested that the discrepancies might arise from capture through unbound states. The capture through unbound states, leading to γ -ray cascades, would contribute to the activation cross section but not to that measured by the spectrum method. In the spectrum measurements only γ -ray transitions to bound states in the final nucleus were taken into

account. It was, however, difficult to explain why no cascades occurred in nuclei with closed neutron shells.

The influence of background neutrons on the activation measurements was shown in experiments performed at the University of Jyväskylä, where the first correction methods were indicated [Va72], and at the University of Lund [Po74]. These methods were developed and applied at Lund to measurements of the capture cross section at 14 MeV for indium [Ma77] and nuclei ranging in mass number from 23 to 197 [Ma80].

A relatively recent review of the measurements at 14 MeV shows that agreement, within the uncertainties, is obtained along the whole mass range between the two methods when proper corrections are applied [Wa80].

For the measurements at 14 MeV the source neutrons are usually obtained from the $^3\text{H}(d,n)^4\text{He}$ reaction ($Q=+17.6$ MeV) with the deuterons accelerated up to 100-200 keV. At these low bombarding energies practically no background neutrons are produced directly by the ion beam. Most of the background neutrons are instead produced by neutron induced reactions [Ma80].

For measurements below 14 MeV the $^3\text{H}(p,n)^3\text{He}$ ($Q=-0.76$ MeV) and $^2\text{H}(d,n)^3\text{He}$ ($Q=+3.27$) reactions are often used as sources. Using these reactions, the background neutrons which affect activation measurements may be divided into two main categories. In the first the neutrons are produced by

the ion beam in primary reactions - (p,n) and (d,n) . These may occur at several places e.g. in the beam line, the entrance window and the beam stop of the gas cell or in the absorption layer and the backing when solid targets are used. To the second category belong neutrons produced in secondary reactions, e.g. (n,n') , and by multiple elastic scattering.

The aim of the experiments reported in paper I was to map these sources of background neutrons; to find ways of minimizing their effects and correcting for the remaining contributions.

Most of the success in performing accurate activation measurements in the MeV region resides in the careful design of the experimental set-up, in the sense that the mechanical structures of the neutron target and surroundings should be kept to a minimum. Moreover, the samples being irradiated should be as small and thin as possible. In most cases the sample size requirements are in contradiction to the need for good counting statistics implying that proper correction methods have to be used.

For the background neutrons produced in the sample the corrections remain fairly constant for the whole energy region considered here (see fig. 2 of paper I). This is due to the fact that for proton-rich nuclei most of the secondary neutrons stem from inelastic scattering which has an almost constant cross section. The activity from these neutrons is proportional to the effective sample thickness.

The same considerations do not however apply to the corrections for the background produced outside the sample. This is different for different neutron targets and also varies with the position of the sample in the experimental area (see figs. 3 and 4 of paper I).

Paper II reports on the application of the methods to measurements of cross sections for ^{197}Au and ^{115}In .

From the experiments it can be concluded that it is worthwhile to pursue measurements of total capture cross sections using the activation method. In addition to their purely scientific interest, correct measurements of capture cross sections may be important in future technological applications, for example in fusion reactors. Provided that proper account is taken of the influence of background neutrons, the method is very simple. Apart from the accelerator it demands modest tools, namely, a germanium detector (or in some cases a β -detector) and a multi-channel analyser. The method is limited to cases where the residual nucleus is radioactive but there are a large number of such cases [Va76]. It is therefore unfortunate that in the energy region 8-14 MeV the measurements become extremely difficult because of deuterium and tritium break-up.

2. GIANT-RESONANCE STUDIES

In 1946-47, Baldwin and Klaiber performed two experiments in which they bombarded several nuclei with high-energy γ rays from a 100 MeV betatron. The first of these experiments was designed to study photo-fission; the second to study the reactions $^{12}\text{C}(\gamma, n)^{11}\text{C}$ and $^{63}\text{Cu}(\gamma, n)^{62}\text{Cu}$ [Ba46], [Ba48]. The cross sections - for photo-fission in uranium and thorium on the one hand and for the neutron decay of ^{12}C and ^{63}Cu on the other - showed the same resonant behaviour as a function of γ -ray energy. From essentially zero, the cross section increased to a conspicuous maximum and decreased strongly again within a few MeV. The position of the resonance was different from case to case.

Goldhaber and Teller proposed to interpret the results as being due to a two-step nuclear process [Go48]. In the first step the γ ray excites a dipole state which is formed as a coherent vibration of all protons against all neutrons in the nucleus. In the second step the collective state deexcites not only by fission or neutron emission but through any of the energetically possible channels.

The existence of resonances in the photo-absorption cross section had been predicted theoretically a few years before the experiments of Baldwin and Klaiber [Mi44]. There had also been some previous experimental indications of the phenomenon [Bot37]. However, the existence of such a resonance, presently known as the Giant Dipole Resonance (GDR), was first recognized with the experiments of Baldwin

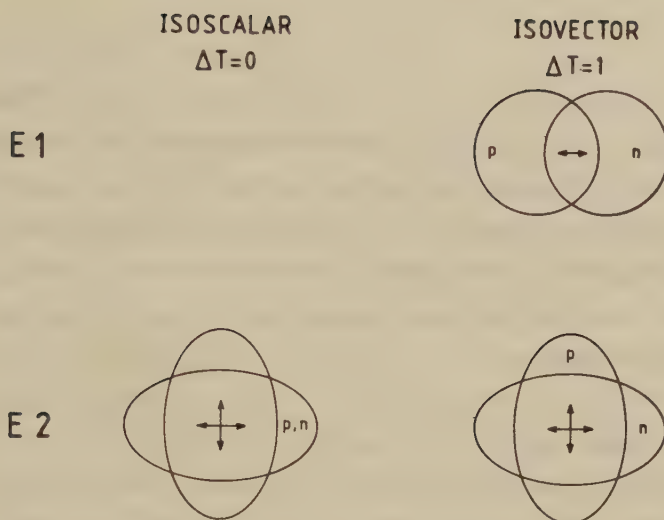


Fig. 2- Schematic representation of the vibrational modes studied in the present experiments.

and Klaiber thus opening up a new field of nuclear research. Experiments in the following years showed that the GDR is a property of all nuclei confirming the interpretation suggested by Goldhaber and Teller:

More recently it has been shown that the nucleus is capable of performing not only collective electric-dipole, E1, vibrations but also other modes; monopole, quadrupole, octupole etc. Fig. 2 shows a schematic representation of the vibrational modes which are of interest here. The E1 vibration is responsible for the GDR. In the electric quadrupole vibrations, E2, protons and neutrons may vibrate in phase - the isoscalar mode - or the neutrons vibrate in one direction while the protons vibrate perpendicularly - the isovector mode.

Most of the early research in the GDR region was performed by means of photo-nuclear reactions because in the forties, and early fifties, betatrons were the most common accelerators available for the production of high-energy probes. With the development of other accelerator types it became possible to use several different probes in giant-resonance studies.

By the middle sixties it became clear that the GDR is excited in proton capture. The cross-section measurements at $E_n = 14$ MeV also indicated that so is the case in neutron capture. In the beginning of the seventies the first neutron-capture experiment was performed which clearly showed the GDR in ^{209}Pb [Be72]. Since then the efforts have been directed towards an understanding of the mechanisms by which the giant multipole states are excited in nucleon-capture reactions.

The remainder of this section is intended as an aid to reading the papers. In subsection 2.1 additional details are given of the experimental arrangements and procedures. Subsection 2.2 deals with a brief presentation of the theoretical models used to describe nucleon-capture reactions. The asymmetry measurements in the region of the isovector quadrupole states are discussed in subsection 2.3.

2.1 EXPERIMENTAL DETAILS

The present experimental set-up used for neutron capture γ -ray spectroscopy at the TLU is shown schematically in fig. 3. The spectrometer can be rotated around the target and fixed in position in steps of 5 degrees. The spectrometer as shown in the figure, was used in the experiments reported in papers IV and V. In the experiment of paper III the anti-coincidence shield (B and C in the figure) was not used. For the experiment reported in paper V the spectrometer was equipped with a new NaI detector. The physical neutron source is referred to in the papers as "gas cell" or "gas target" while the target, number 5 in fig. 3, is denoted "sample".

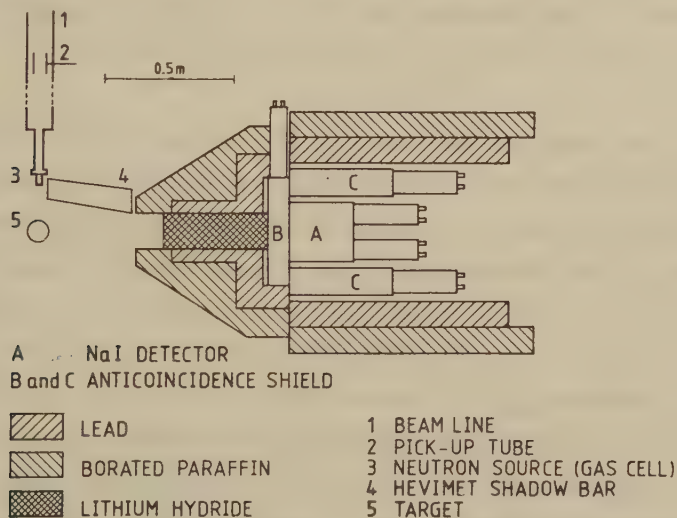


Fig. 3- Schematic representation of the experimental set-up at the TLU. A short pulse (1-3 ns) is generated in the pick-up tube by the passage of the pulsed ion beam. The gas cell is not drawn to scale.

The neutron source

The monoenergetic neutron-production reactions $^2\text{H}(d,n)^3\text{He}$ ($Q=+3.3$ MeV) and $^3\text{H}(d,n)^4\text{He}$ ($Q=+17.6$ MeV) were used in the experiments. The neutron sources can be constructed as solid targets where the gas (whether it is deuterium or tritium) is absorbed in a metallic layer, or as gas cells (see also paper I). Gas cells were exclusively used in the experiments at the TLU. These were brass or stainless steel cylinders, 10 mm in diameter and 25 mm long. The ion beam enters the cell longitudinally through a metallic foil, called entrance window in the papers. The beam is stopped at the other end of the cylinder which consists of a 0.8 mm thick gold disc. The entrance window is only thick enough, a few μm , to withstand the pressure difference between the gas in the cell (about $1.5 \cdot 10^5$ Pa) and the evacuated beam line.

The neutron-production reactions are said to be monoenergetic because, below the deuterium and tritium break-up thresholds, only a single neutron group is produced. However, the neutron-energy distribution over the target has a typical width (100 to 300 keV FWHM) which by far exceeds the width (a few keV) of the ion beam. The spread is due to the kinematics of the reaction (the neutron energy decreases with the emission angle), the energy and angular straggling of the ion beam in passing the foil and its energy degradation and angular straggling in the gas along its path through the cell. The relative importance of each of these contributions depends on the ion-beam energy, the foil thickness and the solid angle subtended by the target at the

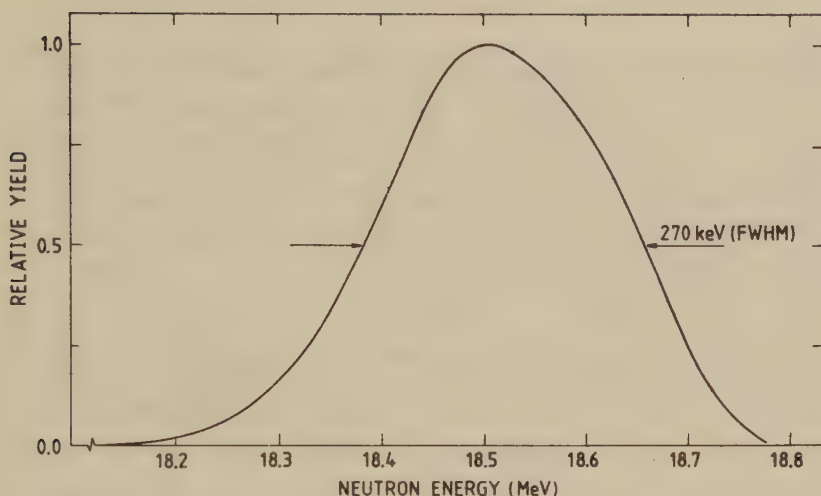


Fig. 4- Monte-Carlo calculation of the neutron-energy spread over a cylindrical target, 6 cm in diameter and 8 cm in length placed 10 cm from the gas cell with its symmetry axis perpendicular to the beam. The ${}^3\text{H}(\text{d},\text{n}){}^4\text{He}$ reaction, $E_d=4.5$ MeV, is assumed in the calculation. The entrance window was a 25.6 mg/cm^2 molybdenum foil and the gas pressure was about $1.5\cdot 10^5$ Pa.

cell. At the energies considered in the experiments the main contribution to the energy spread comes from the kinematic effect. Fig. 4 shows a typical neutron energy distribution calculated with a Monte-Carlo computer program.

Background reduction and separation

The most serious problem in measurements of the prompt γ rays following neutron capture is the intense neutron background. The direct and room-scattered fluxes are attenuated and energy degraded by the hevimet shadow bar (90% tungsten) and the heavy shielding of paraffin and lead around the detectors. However, it is not possible to completely

eliminate the neutrons which are scattered by the target towards the NaI detector. The target-scattered flux is reduced by the lithium hydride in the collimator hole. Owing to the large neutron binding energy in ^{128}I and ^{23}Na , 6.83 and 6.96 MeV respectively, even a small flux would disturb most measurements.

However, the distance between the target and the NaI detector was, in all cases, larger than 1 m. The time between the arrival of γ rays and the arrival of 27 MeV neutrons is then longer than 11 ns. This is sufficient to discriminate against neutron events in the NaI detector if appropriate time-of-flight technique is used. The beam was pulsed at 2 MHz and bunched to a width of approximately 3 ns (FWHM). Fig. 3 of paper V shows time-of-flight spectra obtained with the reaction $^{89}\text{Y}(n,\gamma)^{90}\text{Y}$ at various neutron energies. The time scale is about 1 ns per channel. We may note from the figure that despite the decreasing ratio between the number of γ -ray and neutron events with increasing neutron energy, the separation between the peaks is complete in all cases.

The anti-coincidence shield

The response-line shape for high-energy γ rays in a large NaI crystal is characterized by a gaussian distribution and an exponential tail which is due to the escape of radiation from the crystal. The tail can be suppressed, at the expense of efficiency, if the escaping radiation is detected and the signals are used to veto the corresponding events in the NaI

detector. This is accomplished by the anti-coincidence shield shown in fig. 3 which consists of two plastic scintillators placed in front (B) and around (C) the NaI detector. Fig. 1 of paper V shows a response function obtained for the present NaI detector with the anti-coincidence shield. A second, but by no means less important, function of the shield is to discriminate against cosmic-ray events. Most of the cosmic-ray background reaching the experimental set-up is in the form of muons which deposit large amounts of energy in the detectors.

2.2 THE THEORETICAL MODELS

Nuclear reactions in the MeV region are generally divided, regarding the mechanisms of the process and the time taken to reach the final state, into two extreme categories: the compound-nucleus (CN) and direct reactions. Both models, however, predict too low a cross section in the GDR region. Several theoreticians proposed a semi-direct reaction mechanism which considers capture via the excitation of the giant multipole states.

In the compound-nucleus model, first proposed by N. Bohr [Bo36], the reaction proceeds by two independent steps. In the first the neutron is absorbed by the target nucleus and the excess energy distributed amongst many nucleons. The state lives of the order 10^{-18} to 10^{-16} seconds which is a long time compared with the 10^{-22} seconds approximately taken by a 1 MeV neutron to traverse the nucleus. Within this time the state "forgets" how it was formed meaning that

the results are, to take an example, the same whether an α particle is absorbed in ^{85}Rb or a proton in ^{88}Sr to form a certain compound state in ^{89}Y . The decay of the compound state is purely statistical. It is worth noting that compound states have definite quantum numbers, namely the total angular momentum J , its z component J_z , the parity π and energy E_x , which must be conserved. According to the independency hypothesis the cross section for γ -ray emission is given by

$$\sigma(n, \gamma) = \sigma(E_x, J, J_z, \pi) \cdot P_\gamma \quad (1)$$

where $\sigma(E_x, J, J_z, \pi)$ is the cross section for the formation of a compound state with the indicated quantum numbers and P_γ is the probability for the formation of the single-particle bound state $|\Psi_{nlj}\rangle$ in the residual nucleus through a single transition.

In the direct reaction mechanism the neutron enters directly a single-particle state $|\Psi_{nlj}\rangle$ of the residual nucleus while the target core remains unexcited. The process takes a time of the order 10^{-22} seconds thus being much faster than the compound-nucleus process. The transition amplitude T_d is given by

$$T_d \sim \sum_L \langle \Psi_{nlj} | d_L(r) | \chi^+ \rangle \quad (2)$$

where $|\chi^+\rangle$ is the continuum-state wave function, L the multipolarity of the transition and $d_L(r)$ the single-

particle multipole operator. The cross section for the direct capture alone is given by

$$\sigma_d \sim |T_d|^2 \quad (3)$$

The semi-direct amplitude is given by a similar expression

$$T_{sd} \sim \sum_{L\tau} \langle \Psi_{nlj} | O_{L\tau}(r) | \chi^+ \rangle \quad (4)$$

where the operators $O_{L\tau}(r)$, now, must account for the excitation of the intermediate giant state of multipolarity L prior to γ -ray emission. The isovector ($\Delta T=1$) and the isoscalar ($\Delta T=0$) modes are denoted by $\tau=1$ and $\tau=0$, respectively. The isoscalar quadrupole and higher order modes are weakly excited in neutron capture (see paper III).

The cross section for capture into the single-particle state $|\Psi_{nlj}\rangle$ is proportional to

$$\sigma(n, \gamma) \sim |T_d + T_{sd}|^2 \quad (5)$$

where the effects of interference are taken into account. The semi-direct amplitudes are derived using time-dependent perturbation theory which leads to

$$T_{sd} \sim \sum_{L\tau} \langle \Psi_{nlj} | \frac{h_{L\tau}(r)}{E_\gamma - E_{L\tau} + i \frac{\Gamma_{L\tau}}{2}} | \chi^+ \rangle \quad (6)$$

where $E_{L\tau}$ is the resonance energy, E_γ the γ -ray energy and $\Gamma_{L\tau}$ the resonance width. The main difficulties, since the sixties, have been to find an appropriate expression for the perturbation, i.e. for the particle-vibration coupling $h_{L\tau}(r)$. The early calculations used a real, surface-peaked form

$$h_{11}(r) \sim V_1 \frac{df(r)}{dr} \quad (7)$$

where V_1 is the depth of the surface symmetry potential and $f(r)$ is the Woods-Saxon form factor. With this form neither the shape nor the magnitude of the GDR was reproduced by the DSD model. Such a coupling implies that the neutrons and the protons are considered as "two inter-penetrating incompressible fluids" [Go48]. Another type of coupling considers the motion of proton and neutron fluids within a fixed sphere [Go48] which leads to a volume form

$$h_{11}(r) \sim V_1 r f(r) \quad (8)$$

The introduction of a volume form in the model was proposed [Lo73] which turned out to provide better fits to $^{208}\text{Pb}(n,\gamma)^{209}\text{Pb}$ data in the GDR region [Be72]. However, neither of these coupling forms reproduced the symmetric shape of the GDR shown by experiments. The real forms, rather, showed constructive interference above and destructive below the resonance energy.

The introduction, in addition to the volume form, of an imaginary part of surface type [Sa72], [Pot73]

$$h_{L\tau}(r) \sim r^L [V_1 f_r(r) - iW_1 4b \frac{df_i(r)}{dr}] \quad (9)$$

restored the symmetric shape of the resonance. W_1 is the depth of the imaginary symmetry potential and b is the diffuseness of the imaginary Woods-Saxon form factor. Equation (9), where we note the extension to multipoles higher than $E1$, was used in the experiments. A disturbing feature is the large depth, W_1 , of the imaginary term needed to fit the data, 40, 80 and 140 MeV for capture in ^{40}Ca , ^{89}Y and ^{209}Pb , respectively. As yet, there does not exist a complete physical interpretation of such a large imaginary term.

The experiment of paper III was undertaken with the primary objective of investigating whether compound-nucleus capture would imply lower values of W_1 to fit the data. Capture through the compound-nucleus mechanism dominates below $E_n = 5$ MeV and semi-direct processes dominate above 6 MeV. The cross-section results of compound-nucleus and DSD model calculations were added in the experiment of paper III. In the region between these extremes interference effects might, however, be significant.

2.3 ASYMMETRY MEASUREMENTS

Asymmetry measurements were carried out to study the isovector giant quadrupole resonance (IVGQR) in ^{41}Ca and ^{90}Y . While the GDR is well pronounced in the excitation functions at 90 degrees, the IVGQR is only weakly excited. This may be deduced from fig. 1 of paper IV where the isovector E2 is located at an excitation energy of about 32 MeV in ^{41}Ca . Despite this, the IVGQR may be revealed in the angular distributions of γ rays. The γ -ray yield, $I(\theta, E)$, at angle θ and energy E , can be described by a Legendre polynomial expansion, namely

$$I(\theta, E) \sim 1 + \sum_{i=1}^{2L} a_i(E) P_i(\cos\theta)$$

where L is the highest multipolarity present in the radiation. The presence of odd polynomials in the expansion indicates the interference between radiation of opposite parity. Rather than measuring "complete" angular distributions, e.g. in steps of 5 degrees, the interference may be studied in "three-angle" measurements at 55° , 90° and 125° with respect to the beam. From the measurements the asymmetry values A_1 and A_2 defined as

$$A_1 = \frac{I(55^\circ) - I(125^\circ)}{I(55^\circ) + I(125^\circ)}$$

and

$$A_2 = 2 - \frac{4I(90^\circ)}{I(55^\circ) + I(125^\circ)}$$

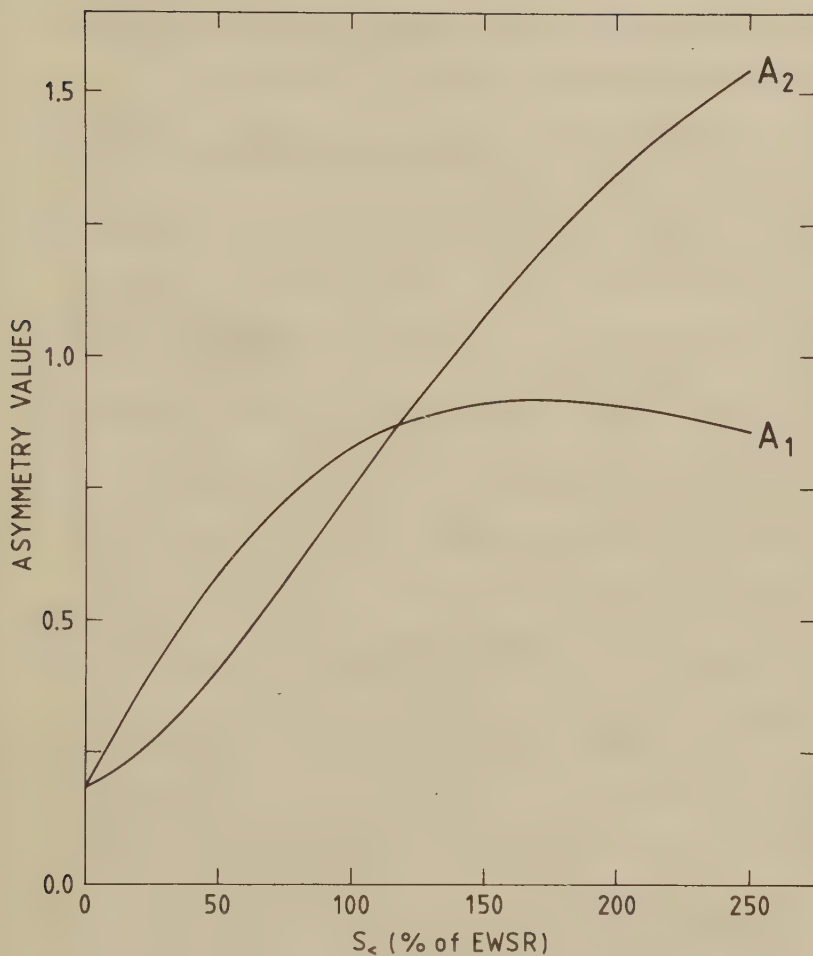


Fig 5- DSD model predictions of asymmetry values as a function of resonance strength, S_c . The asymmetry values were calculated with the same parameters as in fig. 5 of paper V. The A_2 curve has been displaced by an additive constant chosen so as to give $A_2 = A_1$ for $S_c = 0\%$ of the energy-weighted sum rule (EWSR).

can be calculated at each energy. The experimental values were compared with those predicted by the DSD model.

The A_1 values for both calcium (paper IV) and yttrium (paper V) show markedly the effects of interference. For the $2d_{5/2}$ ground state of yttrium the experimental A_1 increased to large values where the corresponding DSD model predictions as a function of resonance strength, S_c , become saturated. On the other hand the model predicts large variations of A_2 with strength. This is shown in fig. 5 where DSD predictions for both A_1 and A_2 are plotted as a function of the fraction of EWSR exhausted by the resonance. The calculations of fig. 5 were performed for a neutron energy of 23 MeV, i.e. near the maximum of the A_1 curves shown in paper V. For γ -ray transitions to the ground-state doublet of ^{90}Y , accurate measurements of both A_1 and A_2 in the whole region of the IVGQR would provide better tests to the DSD model predictions. This was not possible in the present experiment but might be possible in a near future either using a more efficient γ -ray detector or several detectors simultaneously.

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ACTIVATION MEASUREMENTS

PAPER I

THE INFLUENCE OF BACKGROUND NEUTRONS ON (n, γ) ACTIVATION MEASUREMENTS IN THE NEUTRON ENERGY REGION 2.0-7.7 MeV

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Sources of errors in the measurement of MeV neutron capture cross sections with the activation technique have been investigated using the reaction $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$. The main problems are caused by low-energy background neutrons produced by charged-particle reactions (e.g. (p, n) and (d, n) reactions) in the target material and secondary neutrons from nonelastic reactions (e.g. (n, n') and (n, np) reactions) in the sample and surrounding materials. Low-mass target-sample assemblies have been constructed to reduce the influence of secondary neutrons. Methods to correct for the background neutrons have been developed and applied to cross-section measurements for the reaction $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$ in the neutron energy range 2.0-7.7 MeV. The cross section values are significantly lower than previous results.

1. Introduction

Capture cross section measurements using the activation technique in the MeV region appear to be difficult primarily due to accompanying background neutron sources. On the average, the background neutrons are of a much lower energy than the primary neutrons. Since generally the (n, γ) cross section increases rapidly with decreasing neutron energy this means that even a small contamination by background neutrons can seriously disturb the measurements.

Sources of background neutrons can be divided into two categories. One type concerns secondary, low-energy neutrons that are produced by (n, n') , (n, np) and $(n, 2n)$ reactions in the sample and in the material of the surrounding structures in the target-sample assembly. This background of secondary (tertiary, quaternary, etc) neutrons is known to be troublesome in measurements at 14-15 MeV. Measurements [1-5] show that the results of early activation experiments are in error; in some cases by more than a factor of ten. Numerical estimates indicate that secondary neutrons may also significantly disturb the (n, γ) activation measurements in the energy region below 10 MeV.

The other type of background is related to the neutron-source reactions. In our measurements we have utilized the reactions $\text{T}(p, n)^3\text{He}$ and $\text{D}(d, n)^3\text{He}$ for the production of monoenergetic neutrons. The projectiles may, however, also generate a background of primary neutrons from (p, n) or (d, n) reactions in the target backing, slits etc.

This report describes activation measurements for $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$ in the energy range 2.0-7.7 MeV with

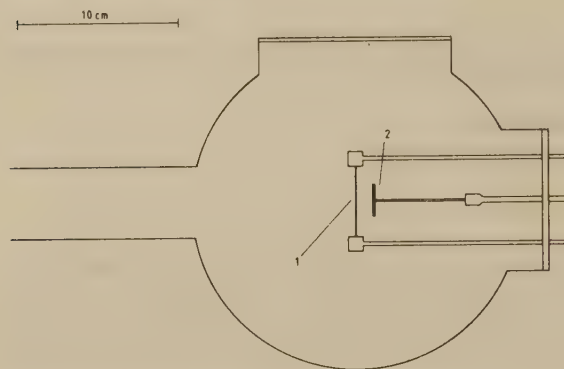
the objective being to investigate the contributions of background neutrons and to find methods which can be used to correct for these contributions in capture cross-section measurements.

The reaction $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$ has been chosen for the investigations because it offers favourable experimental conditions. The $^{116\text{m}}\text{In}$ decay has a suitable half-life ($T_{1/2} = 54.2$ min) and yields a γ -ray, $E_\gamma = 1293$ keV, which is easy to detect. Furthermore, the capture cross section for low-energy neutrons is rather large so the activation yield is sensitive to low-energy background neutrons. It is also an advantage that inelastic neutron scattering of ^{115}In excites a metastable state at $E_\gamma = 336$ keV with $T_{1/2} = 4.5$ h. The cross section for this reaction is known to increase with energy above the threshold up to about 2.4 MeV and then to become almost constant with energy [6]. Because it is a threshold reaction it is not sensitive to low-energy background neutrons, and hence the reaction can be used as a reference reaction in the activation studies.

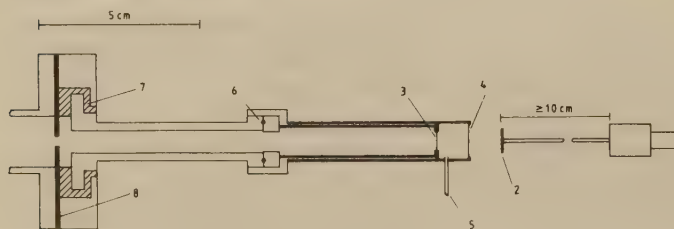
2. Experimental arrangement and procedure

The experimental arrangement has been described elsewhere [7,8] and, therefore, only a short description of the relevant features will be given here. Monoenergetic neutrons were produced either by the reaction $\text{T}(p, n)^3\text{He}$ or by $\text{D}(d, n)^3\text{He}$ with the protons and the deuterons being accelerated by a 3 MV Pelletron tandem accelerator. The beam was focused onto the target with a beam spot of a diameter of less than 3 mm. The current was typically 0.5 μA . The beam conditions were

a) SOLID TARGET ARRANGEMENT



b) GAS TARGET ARRANGEMENT



- | | |
|--------------------|-------------------------|
| 1. SOLID TARGET | 5. GAS INLET |
| 2. SAMPLE | 6. O-RING |
| 3. MOLYBDENUM FOIL | 7. INSULATOR |
| 4. GOLD BEAM STOP | 8. TANTALUM COLLIMATORS |

Fig. 1. The experimental arrangement for (a) the solid tritium and deuterium targets and (b) the deuterium gas target.

checked during irradiation with the aid of two collimators along the beam line. We required that the current on these collimators be less than 1% of that on the target.

Both solid targets and a deuterium gas-target arrangement were used in the measurements, but with different geometries as illustrated in fig. 1. The irradiation of the indium samples with neutrons from the solid

Table 1
Properties of the different target arrangements used in the measurements

Target type	Reaction	Backing/beam stop		Absorption layer		Target denotation
		Material	Thickness [mm]	Material	Thickness [mg/cm ²]	
Solid	T(p,n)	Al	0.5	Ti(nat)	1.8–2.4	T(Ti + Al)
	T(p,n)	Au	0.2	⁹⁰ Zr	1.8–2.4	T(⁹⁰ Zr + Au)
	D(d,n)	Au	0.2	Zr(nat)	1.8–2.4	D(Zr + Au)
Gas	D(d,n)	Au	0.45	—	—	—

targets took place in a target chamber designed to minimize the amount of material around the target-sample region, thereby reducing the production of background neutrons [4]. Details of the targets are summarized in table 1. The solid targets consisted of an absorption layer in which tritium or deuterium was absorbed, evaporated onto a backing. In order to determine the background from neutrons produced by (p,n) or (d,n) reactions in the backing and absorption materials and in the collimators along the beam line, measurements were also made with targets with natural hydrogen replacing ^3H or ^2H . These targets, which we call "empty targets", were prepared in the same way and at the same time as the "active" targets.

The deuterium gas target was also constructed in such a way that there is little structural material between the neutron source and the irradiated sample and in the immediate surroundings of the target sample assembly. The deuterium gas cell is a tube 1 cm in length and approximately 1 cm in diameter made of 0.2 mm stainless steel with a 0.25 mm thick gold beam stop which is soldered onto the inner wall of the tube. Local impurities on the surface of the beam stop (probably from the soldering) caused disturbing variations in the background with the cell empty. Therefore, another 0.2 mm gold disc was inserted in front of the original beam stop. The entrance foil is attached to the cell by means of a hollow piston. Two thin ring-shaped indium seals, one on each side of the entrance foil, are used to seal the system. A 4.2 mg/cm² molybdenum foil has been used in the experiments.

The indium samples used in the measurements were shaped as small discs with diameters ranging from 5 to 20 mm. The thicknesses varied between 0.2 and 1.9 g/cm². The irradiation times were typically 0.5–1.5 h. The γ rays from the induced activity (see table 2) were detected in Ge(Li) detectors. The determination of the detector efficiency and correction for self-attenuation and summing effects have been described elsewhere [7].

The capture cross sections were determined relative to the cross section of the $^{115}\text{In}(n,n)^{115\text{m}}\text{In}$ reaction, which means that neither the neutron flux nor the detector efficiency have to be measured absolutely. Furthermore, it is advantageous to utilize a reference reaction which is built in to the sample in such a way that

the irradiation and analysis geometries are the same for the sample and the reference.

3. Results and discussion

3.1. Background from primary neutrons

The background of primary neutrons from (p,n) and (d,n) reactions was determined from the induced (n, γ) activity with the sample placed in the forward direction with respect to the ion beam.

For the different target arrangements, the (n, γ) activation yield from the source reaction, Y_s , and from the corresponding empty target, Y_b , were measured and the ratio, Y_s/Y_b , is plotted in fig. 2 as a function of the neutron energy of the source reaction. For conventional T(Ti + Al) targets the ratio decreases rapidly with energy above $E_n \approx 4.2$ MeV. The drop is primarily due to the (p,n) threshold of the most abundant titanium isotope, ^{48}Ti (73.9%), which causes a sharp rise in the background yield and determines the upper limit of the useful energy range for this target arrangement.

It was expected that tritium targets with ^{90}Zr evaporated onto a gold backing would be much better since the $^{90}\text{Zr}(p,n)$ threshold is high ($E_p = 6.9$ MeV) which means that below this energy [corresponding to $E_n = 5.9$ MeV for the T(p,n) reaction] few background neutrons should be generated by these targets. This was, however, not the case and it seems likely that additional impurities were present. Instead it appears that the D(d,n)³He reaction ($Q = +3.3$ MeV) is the best source for energies above 4 MeV. In particular the deuterium gas target allows for an extension of the useful energy range by several MeV. The signal-to-background ratio may be improved by increasing the gas pressure and cell length. In the present application, the pressure is as high as the molybdenum foil can withstand over reasonable run periods and the cell length is limited by the need for small target-sample distances because of the influence of secondary neutrons (see sect. 3.2.2).

The useful energy range for a target system is closely related to the question of how precisely the background can be determined by the measurements with the empty targets. The solid empty targets were manufactured, as

Table 2
Decay data for the γ -rays utilized in the present work

Reaction	Energy [keV]	Half-life [s]	Intensity ^{a1} [%]	Ref.
$^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$	1293.54	3247 ± 3	85 ± 2	[9,10]
$^{115}\text{In}(n,n')^{116\text{m}}\text{In}$	336.0	16150 ± 14	45.9 ± 0.3	[11]
$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	411.80	232848 ± 173	95.55 ± 0.08	[11]

^{a1} Photons per 100 decays of the reaction product nucleus.

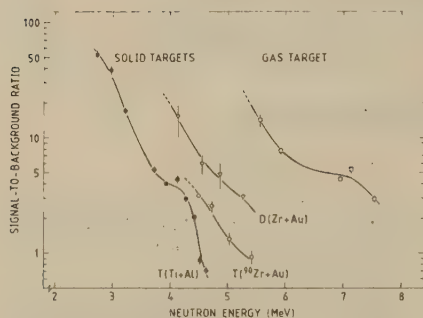


Fig. 2. Signal-to-background ratios from activation-yield measurements for the $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$ reaction for the different target arrangements used. The lines are drawn to guide the eye.

mentioned in sect. 2, in the same way and at the same time as the tritium and deuterium targets. They were also treated in the same way afterwards, i.e. they were exposed to the same proton or deuteron bombardment. The uniformity of the targets was found to be quite good and the reproducibility of the background yield was typically better than 10%. If this value is taken as the uncertainty in the background, the (n, γ) cross section for a signal-to-background ratio of unity will have an uncertainty of $\pm 10\%$ from this source alone. In general, this is not acceptable and one usually requires the ratio to be at least better than 2 or 3. This requirement then limits the useful range for the $\text{T}(\text{Ti} + \text{Al})$ target to $E_n < 4.4$ MeV, for the $\text{T}(\text{Zr} + \text{Au})$ target to $E_n < 4.8$ MeV and for the $\text{D}(\text{Zr} + \text{Au})$ target to $2.5 < E_n < 5.4$ MeV.

With solid targets there always remains the uncertainty, despite all precautions, that the empty target may not represent an adequate background target. To a large extent this uncertainty is removed with the application of a gas target since the background from (d, n) reactions in the entrance foil and the beam stop can be determined with the gas-cell empty or filled with H_2 gas. Either procedure gives the same background yield at the energies considered here.

The most difficult problem with the gas target is the background related to impurities in the D_2 gas itself. The gas used was stated to have a purity of better than 99.4%, with nitrogen being the most abundant contaminant (except for hydrogen which does not affect the measurements). Measurements with the cell filled with nitrogen showed that a content of 0.6% nitrogen in the deuterium gas would give a contribution of more than 45% to the activation yield for energies above 7 MeV. Fortunately the purity of the gas was higher than stated. In an analysis performed using gas chromatography, it

was found that nitrogen was the most abundant impurity with a content of 24 ppm. The contribution to the yield from such a small contamination is less than 1% above 7 MeV.

3.2. Background from secondary neutrons

3.2.1. Background produced inside the sample

As described in a previous report [4] the influence of secondary neutrons from various sources can be determined by varying the experimental parameters. One important source is (n, n') reactions within the sample itself. It can easily be shown that for thin samples the correction due to secondary neutrons is approximately proportional to the thickness of the sample. Hence, this contribution may be studied by varying the sample thickness. This is illustrated in fig. 3.

The dashed lines in the figure are linear fits to the experimental data. It is found that the slopes of the lines are the same for the different neutron energies, except for $E_n = 4.5$ MeV. Here, the slope is about two standard deviations from the average value. However, there is no reason to believe that the deviation is anything but statistical.

The solid line in fig. 3 represents the results of model calculations. The model used in the calculations of the contribution of secondary neutrons has been described previously [4], and is based on the assumption that the secondary neutrons are generated uniformly in the sam-

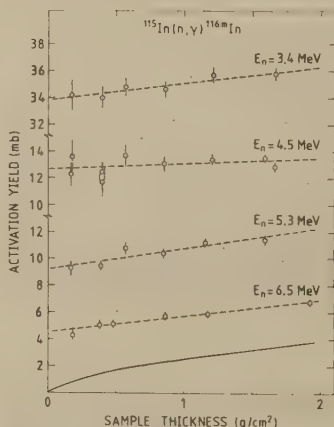


Fig. 3. Activation yield for different sample thicknesses at several primary-neutron energies. The dashed lines are linear least-squares fits to the experimental data. The solid line shows the contribution of secondary neutrons obtained from model calculations. Only statistical uncertainties are given.

ple. The model is based on formulas, derived by Carlvik [12], for the probability that such a neutron will undergo a collision on its way out of the sample. The energy distribution of the neutrons from (n,n') reactions was estimated from the statistical model and the cross sections, needed in the calculations, were taken from ref. [13]. The line in the figure comes from calculations at $E_n = 3.4$ MeV but the results at other energies in the range 2.0–7.7 MeV are very nearly the same. The slope of the line agrees quite well with the experimental results. The calculations indicate that the contribution of secondary neutrons should not be exactly linear with thickness but should drop faster to zero at smaller thicknesses. The non-linearity is, however, too small to be verified experimentally with the present arrangement.

3.2.2. Background produced outside the sample

The most important sources of secondary neutrons outside the sample are (n,n') reactions in structural materials near the target-sample assembly and neutrons scattered from the walls of the room. The influence of these background neutrons may be determined by studying the distance dependence of the activation yield, $Y(n, \gamma)$. To see this, consider the (n, γ) activity, $A(n, \gamma)$, induced in a sample:

$$A(n, \gamma) \propto \sigma_0 \langle \Phi_0 \rangle + \sigma_{\text{sec}} \langle \Phi_{\text{sec}} \rangle + \sigma_{\text{room}} \langle \Phi_{\text{room}} \rangle. \quad (1)$$

The first term is due to the capture of the primary neutrons and the other terms account for the capture of secondary neutrons. The different neutron fluxes are represented by Φ and the corresponding cross sections by σ . The subscript "sec" represents neutrons scattered inelastically in the structural materials near the target and the sample, and "room" denotes neutrons generated elsewhere in the room.

The activation yield is obtained by dividing $A(n, \gamma)$ by the flux of primary neutrons, $\langle \Phi_0 \rangle$. In practice $\langle \Phi_0 \rangle$ is determined by utilizing the reaction $^{115}\text{In}(n, n')^{115\text{m}}\text{In}$ for which the influence of secondary neutrons is negligible. One then obtains

$$Y(n, \gamma) = \sigma_0 + \sigma_{\text{sec}} \frac{\langle \Phi_{\text{sec}} \rangle}{\langle \Phi_0 \rangle} + \sigma_{\text{room}} \frac{\langle \Phi_{\text{room}} \rangle}{\langle \Phi_0 \rangle}. \quad (2)$$

For simplicity, assume that the source of primary neutrons is a point source and, hence, that Φ_0 varies with distance, r , as r^{-2} . The room-scattered neutrons should be nearly uniformly distributed in the vicinity of the target-sample area, i.e. Φ_{room} is constant, whereas the secondary neutrons from (n,n') reactions in the structural materials, Φ_{sec} , should have a distance dependence between these two extremes. Thus, we may roughly estimate

$$Y(n, \gamma) = \sigma_0 + a f(r) + b r^2. \quad (3)$$

When applying eq. (2) to derive the cross section, σ_0 ,

one must calculate the average neutron flux, $\langle \Phi_0 \rangle$, from an extended source over the sample. This calculation was made numerically with the aid of a Monte Carlo program. The program was also used to estimate the second term in eq. (2) which accounts for the contribution of secondary neutrons from structural materials. It is assumed, as above, that the neutron background from room-scattered neutrons does not depend on the distance (in the target-sample region) so the distance dependence of the third term in eq. (2) comes entirely from the denominator, $\langle \Phi_0 \rangle$. Hence, the magnitude of this contribution can be determined by fitting the experimental data. The curves in figs. 4 and 5 show fits made using this procedure. The shaded area represents the contribution to the activation yield from secondary neutrons produced in the beam stop, and the unshaded area above shows the contribution from room-scattered neutrons.

The contribution of room-scattered neutrons was rather large in our first set of measurements (with the solid T(Ti + Al) targets). Examples of the results for these targets are shown in fig. 4. The experimental results can be well fitted by r^2 curves which indicates a dominant contribution of room-scattered neutrons. We tried to reduce this strong influence on the yield by surrounding the scattering chamber in a cadmium cover in order to capture the thermal neutrons but observed only a small reduction in the yield.

The position of the target-sample assembly in the room appeared to be of great consequence in influencing the room-scattered neutrons. The irradiations were performed in a room of dimensions $5 \times 5 \times 5$ m³. For the reason of good beam optics, the neutron target in the measurements described above was positioned only

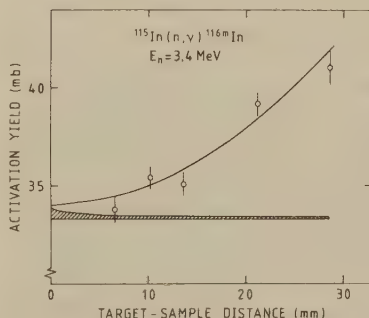


Fig. 4. Activation yield for different source-to-sample distances, r , for the first set of measurements with T(Ti + Al) targets. The curves represent fits made according to the procedure described in the text. The error bars represent statistical uncertainties.

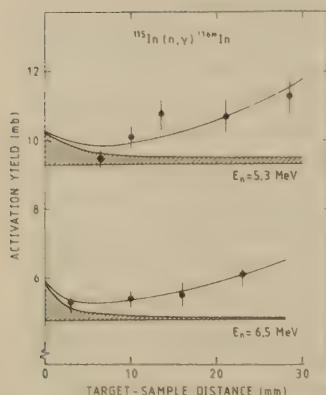


Fig. 5. Activation yield for different source-to-sample distances. Solid deuterium targets were used in the 5.3 MeV measurements and the gas target was used in the 6.5 MeV measurements. The target-sample distance was defined as being the distance from the beam stop to the sample. The curves represent fits made according to the procedure described in the text. Only statistical uncertainties are given.

about 1.5 m from the wall in the forward direction. With this arrangement, the correction due to the room-scattered neutrons amounts to about 1.6 mb at distance of 10 mm (see fig. 4) which may be tolerable below $E_n = 4.5$ MeV where $\sigma_c > 10$ mb. At higher energies, however, these background neutrons would seriously limit the accuracy of the cross-section determination. Hence, we decided to shorten the beam line by approximately 1 m at the expense of beam quality. The result is that it requires more work to obtain a satisfactory beam spot on the target but, in return, a much weaker influence from room-scattered neutrons is obtained. This can be seen in the distance dependence of the activation yield, examples of which are shown in fig. 5. One notes that there is a much weaker dependence both in the case of the solid target at $E_n = 5.3$ MeV and in the case of the gas target at 6.5 MeV. In both cases the correction due to room-scattered neutrons amounts to approximately 0.4 mb at a distance of 10 mm.

Several measurements were performed to study the influence of secondary neutrons produced in the beam stop, gas-target tube and other structural materials in the target-sample area. This contribution is relatively small owing to the design of the target arrangement with little material in the immediate target-sample vicinity. As an example, the results of measurements with a gold disc, 1 cm in diameter, placed 5 mm from the beam stop of the gas cell are shown in fig. 6. The thickness of the disc was varied up to 0.95 mm and the

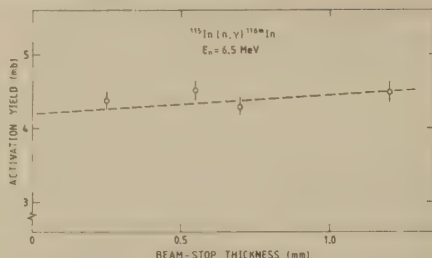


Fig. 6. Activation yield for different thicknesses of the beam stop of the gas cell. The dashed line represents the contribution obtained from calculations.

(n, γ) activity was measured with an indium sample 15 mm from the beam stop. The dashed line in the figure represents the calculated dependence of the activation yield on beam-stop thickness. From the results it was concluded that the contribution to the activation yield of secondary neutrons from the structural material was 0.20 mb at a distance of 10 mm from the gas cell (with a 0.45 mm thick beam stop).

3.3. Energy dependence

From the results presented above some general conclusions can be drawn concerning the background from secondary neutrons. We consider first the contribution to the activation yield from secondary neutrons produced in the sample itself. The results in fig. 3 indicate that the background yield is essentially independent of the primary-neutron energy in the region studied in this work. Moreover, the model calculations predict that the contribution of secondary neutrons is nearly constant with energy from about 2.5 MeV up to the ($n, 2n$) threshold at 9.0 MeV for ^{115}In .

We found it remarkable that the magnitude of the correction for room-scattered neutrons depends so strongly on the location of the target in the room. The new target location, about 2.5 m from the walls of the room, gives significantly lower background than the previous one. For a given location, the correction is approximately constant with neutron energy and also independent of the target type used.

Thus, our results show that for measurements performed with one and the same target arrangement, located at the same place, the total contribution from secondary neutrons can be considered to be approximately independent of the primary-neutron energy between 2.0 and 7.7 MeV. On the other hand, the capture cross section for ^{115}In drops rapidly with neutron energy (see section 3.4). Hence, the correction due to secondary neutrons will become more important as the neutron energy increases.

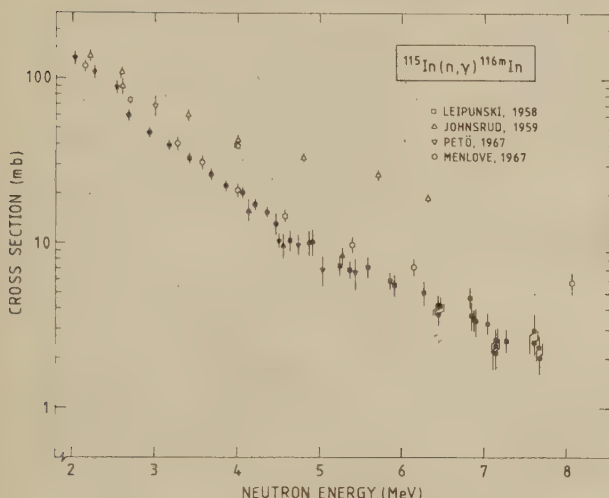


Fig. 7. Cross section for the reaction $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$ as a function of neutron energy. The different target types used in the measurements are ∇ T($^{90}\text{Zr} + \text{Au}$), $\bullet$ T(Ti + Al), $\blacktriangle$ D(Zr + Au) and $\blacksquare$ gas target.

3.4. Capture cross-section measurements

The neutron-capture cross sections were determined for the nucleus ^{115}In in the energy range 2.0–7.7 MeV relative to the $^{115}\text{In}(n, n')^{115\text{m}}\text{In}$ cross section which was taken from ref. [6]. The cross-section results are summarized in fig. 7 together with some previous results [14–17].

The present data agree very well with the results of Menlove et al. [14] for neutron energies below 4 MeV. However, as the neutron energy increases the present results drop significantly below the values of Menlove et al., which tend to be constant (about 6 mb) above 7 MeV. This is a factor of two larger than our values at 7.0–7.7 MeV. Comparison with measurements at 14–15 MeV [4], where the discrepancy is a factor of 6 or more, indicates that Menlove et al. did not adequately account for the background of secondary neutrons. It seems reasonable to assume that sufficient corrections were not applied either in still earlier work [15–17] or in a recent experiment [18].

The cross sections have been corrected for the contribution of secondary neutrons by using the measured dependences on the target-sample distance and the sample thickness. As described in sect. 3.2.1, the thickness corrections were obtained by linearly extrapolating the yield curve to zero thickness. This correction may however be too small. According to the model calcula-

tions, the dependence of the activation yield on sample thickness is not linear for small thicknesses (see fig. 3). A linear extrapolation to zero thickness would then give too small a correction. We have not taken this non-linearity into consideration since it could not be experimentally verified with the present arrangement, whether the effect is real or due to shortcomings of the model. Taking the effect into account, however, would lower the ^{115}In cross sections by 0.5 mb. Thus, the effect would be significant in the higher energy region and must be further studied.

The different types of targets used in the measurements are indicated by different symbols in fig. 7. As has been pointed out above the background problems differ considerably for the different target types. For instance, at $E_n \approx 5.0$ –5.5 MeV the signal-to-background ratio for the gas target is about eight times better than that for the solid D(Zr + Au) targets. In spite of this large variation in the experimental conditions, there is excellent agreement in the cross-section results in the energy regions for which more than one target type was used.

The total uncertainty in the final cross sections amounts to typically 10–20%. The main contributions come from statistical uncertainties (which contain the contribution from the primary-neutron yield measurements as well as the uncertainty in the empty-target yield determination) and from the uncertainty in the

reference reaction cross section. Other contributions are related to uncertainties in the relative detection efficiency, the γ -ray self-absorption and summing effects, the half-lives and the branching ratios. The uncertainty in the determination of the correction for secondary neutrons gives a small contributions to the total uncertainty at lower energies but becomes of major importance at higher energies.

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ACTIVATION MEASUREMENTS

PAPER II

CROSS SECTIONS FOR $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$ AND $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$ IN THE NEUTRON ENERGY REGION 2.0-7.7 MeV

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Abstract: The cross sections for the reactions $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$ and $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$ have been measured with the activation method in the neutron energy region 2.0-7.7 MeV. The influence of background neutrons on the results was studied in considerable detail. The main problems are caused by low-energy neutrons produced by charged-particle reactions in the target material and secondary neutrons from nonelastic reactions in the sample and surrounding materials.

The measured capture cross sections are generally lower than previous results and the deviation tends to increase with increasing neutron energy. The data are also compared with calculations based on the compound-nucleus model and quite good agreement is obtained.

E NUCLEAR REACTIONS ^{197}Au , $^{115}\text{In}(n, \gamma)$, $E = 2\text{--}7.7$ MeV, measured $\sigma(E)$. Compound-nucleus analysis.

1. Introduction

The objective of this work was to measure correct cross sections for the reactions $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$ and $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$ in the neutron energy range 2.0-7.7 MeV. We mean by "correct" that we have tried to find all possible sources of errors in the measurements (in particular from primary and secondary background neutrons), to reduce the influence of these sources, and, finally, to determine their contribution to the result. We have chosen these two reactions for obvious reasons. Since it is adopted as a standard, it is important to measure the neutron-capture cross section for ^{197}Au accurately. The indium reaction is very convenient to use in activation cross-section measurements; its virtues have been emphasised elsewhere¹⁾.

Previous (n, γ) experiments on gold in this energy region have been performed by measuring either the prompt γ -rays²⁻⁴⁾ or the induced activity⁵⁻¹⁰⁾. Several

experiments have previously also been carried out on indium^{5,7,10-12}) in which the induced activity of the metastable state at 1294 keV in ^{116}In was measured. The results from the various experiments differ greatly, in particular in the upper energy range. The first measurements were performed almost 30 years ago and the trend is for the cross-section values to become lower and the differences smaller with time.

The discrepancies no doubt reflect experimental difficulties. In the measurement of prompt γ -rays the low-energy portion of the γ -ray pulse spectrum is masked by γ -rays from e.g. $(n, n'\gamma)$ reactions and the extrapolation of the spectrum to zero pulse height (which is necessary in order to obtain the cross section) becomes increasingly uncertain as the neutron energy increases. Measurements with the γ -ray spectrum method have been extended to neutron energies up to 3.5 MeV. The difficulties in the activation measurements are related to background neutrons from various sources. We have recently concluded a study¹³) of these sources and their influence on activation results.

The experimental data are compared with theoretical calculations based on Hauser-Feshbach theory of compound-nucleus (CN) reactions known to predominate at low neutron energies. The capture cross sections for gold and indium drop rapidly with increasing energy, however, and in the upper range covered in this work, i.e. above 6 MeV, one might expect the CN cross section to be so low that direct reactions may give a non-negligible contribution. Calculations have, therefore, also been made with the direct-semidirect (DSD) model to estimate this contribution.

2. Experimental method

Monoenergetic neutrons were produced either by the reaction $^3\text{H}(p, n)^3\text{He}$ or by $^2\text{H}(d, n)^3\text{He}$ with the protons and deuterons being accelerated by a 3 MV Pelletron tandem accelerator. Several different types of solid targets and a deuterium gas-target arrangement were used for neutron production in the measurements. The target arrangements were designed to reduce the production of background neutrons by minimizing the amount of material in the vicinity of the neutron-producing target and the irradiated sample and by choosing materials with low (p, n) and (d, n) cross sections. We used a variety of indium and gold samples ranging in thickness from 0.2 to 2.0 g/cm² and in diameter from 5 to 20 mm. These were placed in the forward direction with respect to the ion beam at distances varying from 3 mm to 30 mm from the target. By varying the experimental parameters the influence of low-energy secondary neutrons from nonelastic reactions (e.g. (n, n') and (n, np) reactions) in the sample and surrounding materials could be studied. These studies are described in ref. ¹³).

The γ -rays from the induced activity were detected in Ge(Li) spectrometers (see table 1 for decay data). The capture cross sections were determined relative to the cross section of the $^{115}\text{In}(n, n')^{115\text{m}}\text{In}$ reaction. The reference reaction is hence built into the indium sample which is advantageous because the geometries for irradiation

TABLE 1
Decay data for the γ -rays used in the present work

Reaction	Energy [keV]	Half-life [s]	Intensity ^{a)} [%]	Ref.
$^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$	1293.54	$3\,247 \pm 3$	85 ± 2	^{9,10)}
$^{115}\text{In}(n, n')^{115\text{m}}\text{In}$	336.0	$16\,150 \pm 14$	45.9 ± 0.3	¹¹⁾
$^{197}\text{Au}(n, \gamma)^{198}\text{Au}$	411.80	$232\,848 \pm 173$	95.55 ± 0.08	¹¹⁾

^{a)} Photons per 100 decays of the reaction product nucleus.

and γ -ray detection are the same for the sample and the reference. We attached a thin indium disk to each of the gold samples (with the same diameter) so that for gold the reference and sample geometries were also nearly the same. The reference reaction is suitable for the present measurements because the cross section is almost constant with neutron energy over the entire energy range and it has been measured¹⁷⁾ with good accuracy (± 6 –10%). The validity of this procedure was checked at a few energies by measuring the neutron flux with a proton-recoil telescope and the γ -ray activity in an absolute way.

It was concluded from our studies¹³⁾ of background neutrons that the main sources of secondary neutrons are inelastic scattering in the sample itself, in the target beam-stop and in the walls of the experimental area. The correction due to these secondary neutrons was determined from the dependence of the activation yield on sample thickness, beam-stop thickness and target-sample distance. We illustrate this procedure in fig. 1, which shows the influence of secondary neutrons in the sample.

It is generally observed that the dependence on sample thickness is roughly linear for thin samples. In our previous work¹³⁾ we obtained the correction from a linear extrapolation of the yield to zero thickness. However, this procedure is not quite correct, as theoretical calculations¹⁾ show a nonlinear dependence for very small thicknesses. The reason for the nonlinearity is that secondary neutrons produced in a very thin sample, on average, cover a distance within the sample greater than the sample thickness. One may define an "effective sample thickness" as the average distance covered by the secondary neutrons produced in the sample. Fig. 1 shows the activation yield plotted as a function of the effective thickness. The average distance for a given sample was calculated with a computer program simulating a uniformly distributed source of secondary neutrons inside the sample. We note that in this representation the theoretical dependence becomes linear with thickness. The correction obtained from the linear extrapolation of the yield to zero effective thickness is somewhat larger than that previously obtained; the difference is 0.3–0.4 mb for gold and 0.3–0.5 mb for indium.

The influence of secondary neutrons from various sources was measured at different primary neutron energies. The results indicate that the variation e.g. with

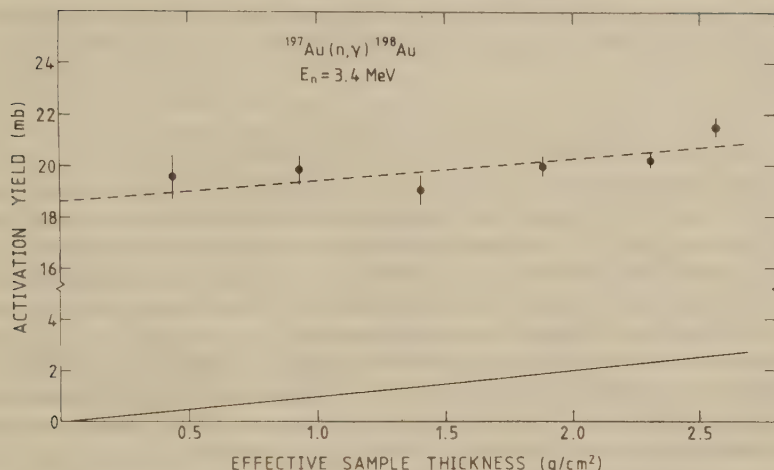


Fig. 1. Dependence of the activation yield for gold on the "effective sample thickness" (see text). The dashed line is a linear least-squares fit to the experimental points. The solid line shows the contribution of secondary neutrons obtained from model calculations. The error bars represent statistical uncertainties only.

sample thickness is approximately independent of the neutron energy. The same was observed for the other experimental parameters. Hence, to a good approximation, the absolute magnitude of the correction for secondary neutrons in a given experimental set-up (i.e. fixed target-sample arrangement) remains the same in the energy range 2.0–7.7 MeV.

The average neutron energy of the primary neutrons hitting the sample was calculated with a computer program simulating the neutron flux incident on the sample. The calculations take into account the energy degradation of the projectile in the target and the variation of the neutron intensity and energy with emission angle. The full-width at half-maximum (FWHM) of the energy distribution was typically 100 keV.

The uncertainty in the obtained capture cross sections reflects uncertainties originating from several sources. The statistical uncertainty (typically 5–10%) contains the contribution from the primary-neutron yield measurements as well as the uncertainty in the empty-target yield determination. The cross section of the $^{115}\text{In}(n, n')^{115\text{m}}\text{In}$ reference reaction has been determined¹⁷⁾ with an accuracy of $\pm(6\text{--}10\%)$. Other contributions are related to uncertainties in the relative detection efficiency (2%), the γ -ray correction factors (1–3%), and the half-lives and branching ratios (1–3%). The correction for secondary neutrons, produced both inside and outside the sample, was typically 1 mb and was determined with an accuracy of about ± 0.4 mb. This uncertainty gives a small contribution to the total uncertainty

at lower energies but becomes of major importance at higher energies. The total uncertainties amount to typically 10–20% both for the ^{115}In and the ^{197}Au cross sections.

3. Calculation of compound-nucleus cross sections

The calculations of the capture cross sections have been performed using the EMPIRE code¹⁸⁾ which is based on the formalism proposed by Tepel *et al.*¹⁹⁾. A complete γ -ray cascade, consisting of transitions between and from the continuum states, as well as transitions between the discrete, known levels, was calculated. The neutron and radiative channels were assumed to be relevant for comparison of the theoretical prescription with the present experiment.

The populations of excited levels with known spins and parities were calculated, and for excitation energies exceeding the highest known level, the density formula of Gilbert and Cameron²⁰⁾ was used to describe the level spectrum. Above a certain excitation energy $E = E_x$, the density of levels of spin J is given by

$$\rho(E, J) = \frac{\sqrt{\pi}}{12} \frac{\exp(2\sqrt{a(E-\Delta)})}{a^{1/4}(E-\Delta)^{5/4}} \frac{2J+1}{2\sqrt{2\pi}\sigma^3} \exp\left(-\frac{(J+\frac{1}{2})^2}{2\sigma^2}\right), \quad (1)$$

and below E_x by

$$\rho(E, J) = \frac{1}{T} \exp((E-E_0)/T) \frac{2J+1}{2\sqrt{2\pi}\sigma^3} \exp\left(-\frac{(J+\frac{1}{2})^2}{2\sigma^2}\right). \quad (2)$$

The parameters used in the calculations were determined according to methods applied by Reffo^{21,22)}. The values of the level-density parameter a follow from the overall systematics, obtained by fitting the resonance sequences of nuclei. The nuclear temperature T , or E_0 which defines the energy dependence of the constant-temperature, low-energy formula (eq. (2)), was extracted by fitting to the step-like dependence of the cumulative number of known discrete levels²¹⁾. The pairing energies Δ were taken from the work of Gilbert and Cameron²⁰⁾. Once a , T (or E_0) and Δ have been fixed, the remaining parameters E_0 (or T) and E_x can be calculated by matching the low-energy and high-energy level density formulae at E_x . The spin dependence of the level density is defined by the spin cut-off parameter σ^2 which has been evaluated from the spins J_i of low excited levels:

$$\sigma^2 = \frac{1}{2N} \sum_{i=1}^N (J_i + \frac{1}{2})^2, \quad (3)$$

where N is the number of known excited levels. For higher excitations we used the Gilbert and Cameron value for this parameter²⁰⁾:

$$\sigma^2 = 0.0888 A^{2/3} \sqrt{a(E-\Delta)}. \quad (4)$$

The radiative widths were estimated from γ -ray strength functions²³⁾ derived from photoabsorption cross sections. This involves fitting the data for the giant dipole

resonance with lorentzian line-shapes and extrapolating to the low-energy region, where experimental data are available. [The procedure is based on the Brink hypothesis²⁴) that the giant resonance built on excited states is the same as that built on the ground state.] The giant resonance data for Au were taken from ref.²⁵) except for the E_γ region below 7 MeV for which the strength function proposed by Earle *et al.*²⁶) was applied. In the case of ^{115}In the phenomenological double-peaked giant dipole resonance strength function was taken from ref.²⁷). The E2 and M1 transitions were assumed to be retarded by one order of magnitude relative to the Weisskopf estimate in agreement with empirical evidence.

The level density parameters a and T , for the compound nuclei ^{198}Au and ^{116}In were slightly adjusted within the uncertainties of the systematics²⁰), in order to simultaneously reproduce the measured radiative width and the average capture cross section at resonance energies. The a -parameters for the residual nuclei after neutron emission were readjusted at 2 MeV neutron energy, where the capture cross section is sensitive to the competitive neutron channel. These parameters, adopted in the calculations, are shown in table 2. They differ from the systematic values, e.g. for ^{116}In by 4.6%, which corresponds to a 20% decrease in the capture cross section. The corresponding deviation of the a -parameter for ^{198}Au by 3.4% causes again a 20% decrease in the cross section. It seems that these changes, propagated according to the error propagation law, best define the uncertainty of our theoretical calculations to a level of about $\pm 30\%$.

TABLE 2
The most important level-density parameters adopted in the present calculations and some of the results obtained

	^{115}In	^{116}In	^{197}Au	^{198}Au
$a^a)$	17.4	17.4	19.9	17.9
a^{adop}	18.2	16.1	19.4	18.5
$T^a)$	0.54	0.55	0.51	0.54
T^{adop}	0.60	0.60	0.52	0.58
E_x^{calc}	4.575	3.798	3.513	4.308
E_0^{calc}	-0.588	-1.331	-0.493	-1.653
$\Gamma_\gamma^{\text{calc}}$		80		90
$\Gamma_\gamma^{\text{exp}}$		75 ± 15		120 ± 20

^{a)} Ref.²⁰).

The j -dependent optical-model transmission coefficients were calculated from the optical potentials, which have been individually fitted to the ^{115}In and ^{197}Au data at 1.5 MeV neutron energy^{28,29}). At higher neutron bombarding energies the energy-dependent optical potential parameters of Willmore and Hodgson³⁰) were applied.

Up to 48 individual levels were accounted for in the calculation of the final populations of states and transitions feeding the isomeric state in ^{116}In . The number of levels accounted for in ^{198}Au and the residual nuclei after neutron emission were lower but exceeded 16 [ref. ³¹]. The results of the calculations are presented in fig. 2. It is worthwhile to note that the calculation (as described) yields a radiative width of 80 meV for ^{116}In and of 90 meV for ^{197}Au at thermal energy, in satisfactory agreement with experimental data ³²).

The influence of the level-width fluctuations on the cross section, which is negligible in the present calculations due to the high number of open channels, was estimated according to the procedure described in ref. ³³).

4. Results and discussion

The results of the present measurements are shown in table 3 and together with the results from previous experiments in fig. 2. In general, the results agree reasonably well in the lower energy region but deviate more and more with increasing energy. This deviation indicates that the problem may be related to the background of low-energy secondary neutrons. It is then of interest to see to what extent these background neutrons have been considered in the various experiments.

The first systematic study of capture cross sections in this neutron-energy region was performed by Johnsrud *et al.* ⁵). They corrected for room-scattered neutrons by measuring the activation yield with the sample positioned at a large distance from the neutron-producing target and assuming a uniform distribution of background neutrons. The correction was rather small (less than 8% at 6 MeV). With a similar irradiation geometry Menlove *et al.* ¹²) obtained a relative correction of about 40% at 6 MeV and suggested that Johnsrud *et al.* did not make sufficient corrections for the effect of room-scattered neutrons. Our results support this suggestion. It also seems plausible that Johnsrud and co-workers did not make adequate corrections for secondary neutrons from other sources.

Our results for $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$ (fig. 1) differ, above 5 MeV, also from those of Menlove *et al.* ¹²). In this case, however, the cause of the difference is not so obvious. The various corrections applied by Menlove are consistent with our results. The only exception may be the correction for the influence of secondary neutrons from the gas-target cell and surrounding material. This background has been observed to be the predominant source of error in older activation measurements at 14–15 MeV [refs. ^{1,34})] and it is possible that this background caused the erroneously high cross-section result (about 6 mb) at 15 MeV obtained by Menlove *et al.* If so, one can explain the difference between the values at lower energies as due to secondary neutrons from this source.

Recent measurements on indium by Kornilov *et al.* ³⁵) at energies between 5.7 and 7.1 MeV agree with the present results. The experimental technique to reduce the influence of secondary neutrons and to correct for contributions from these

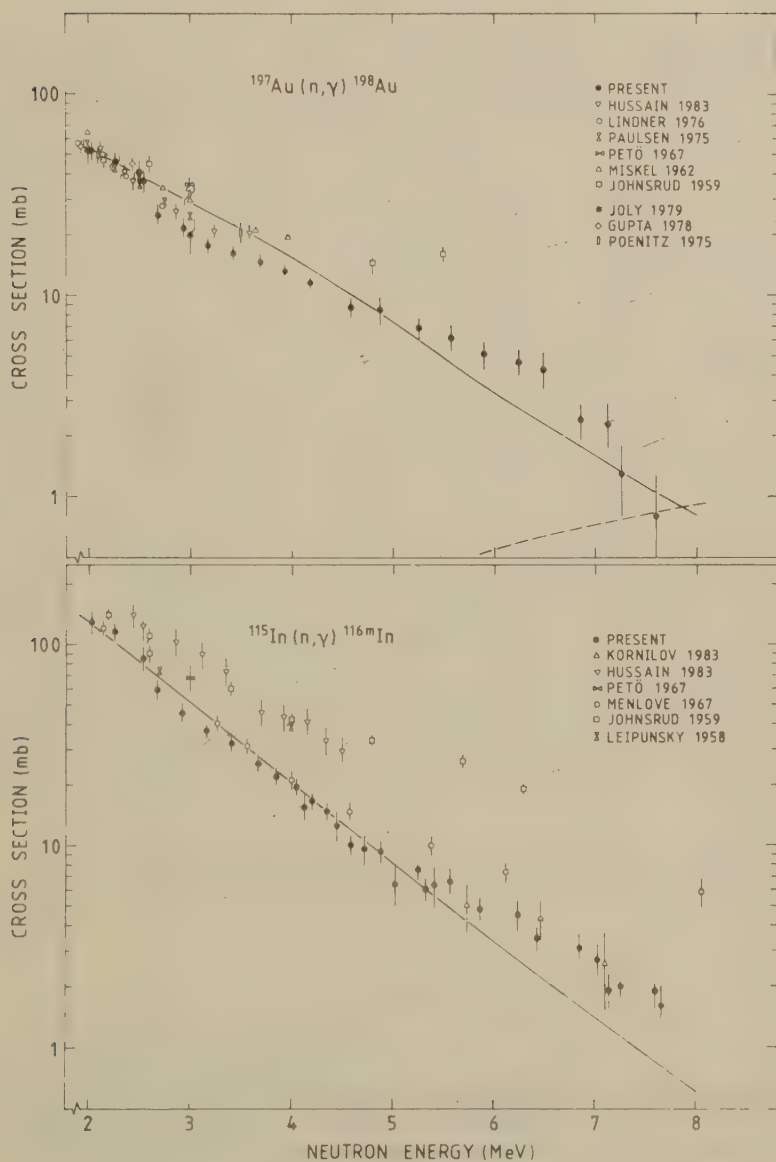


Fig. 2. Cross sections for the reactions $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$ and $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$. The lines represent theoretical calculations according to the compound-nucleus (solid lines) and direct-semidirect (dashed line) models.

TABLE 3

The present capture cross-section results (in mb) and data for the reference reaction $^{17})$

E [MeV]	$^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$		$^{197}\text{Au}(n, \gamma)^{198}\text{Au}$		$^{115}\text{In}(n, n')^{115\text{m}}\text{In}$	
	σ	$\Delta\sigma$	σ	$\Delta\sigma$	σ	$\Delta\sigma$
2.03	130	17	53	6	264	26
2.26	116	15	46	6	309	31
2.54	85	12	37	5	331	33
2.68	59	7	25	3	336	34
2.93	45	5	21.7	2.4	334	33
3.17	37	4	17.8	1.6	332	27
3.42	32	3	16.3	1.5	331	26
3.68	25.5	2.5			328	26
3.69			14.8	1.3	328	26
3.86	22.0	2.2			322	26
3.93			13.2	1.2	320	26
4.06	19.6	2.0			315	25
4.13	15.4	2.4	11.8	1.6	313	25
4.18			11.6	1.1	312	25
4.21	16.5	1.7			311	25
4.36	14.7	1.5			310	25
4.50	10.0	1.1			311	25
4.59	9.8	1.2	8.8	1.1	312	25
4.73	9.6	1.5			315	25
4.87			8.5	1.5	317	25
4.89	9.3	1.2			318	25
5.03	6.4	1.6			321	26
5.26	7.6	0.9	6.9	0.8	327	26
5.35	6.0	0.8			330	26
5.42	6.3	1.7			333	27
5.58	6.6	1.0	6.2	0.9	335	27
5.87	4.8	0.6			338	27
5.90			5.1	0.8	338	27
6.25	4.5	0.8	4.7	0.7	339	20
6.44	3.4	0.5			335	20
6.49			4.3	0.9	333	20
6.85	3.1	0.5	2.4	0.5	315	19
7.03	2.7	0.5			306	18
7.13	1.9	0.4	2.3	0.6	301	18
7.26	2.0	0.5	1.3	0.5	298	18
7.60	1.9	0.4	0.8	0.5	295	18
7.66	1.6	0.4			296	18

neutrons is similar to the methods used in this work. The results from another recent experiment $^{10})$ show large discrepancies. It appears, however, that only the background from room-scattered neutrons was considered in that experiment and it seems likely that adequate corrections were not applied.

The early inconsistencies in the activation results for gold at energies below 3 MeV have, to a large extent, been resolved in the experiments by Paulsen *et al.* $^{8})$ and

Lindner *et al.*⁹⁾). Our results are in accordance with the results from these experiments. Comparison with the results from prompt γ -ray measurements^{2, 4)} shows quite good agreement although the cross sections at 3.0 and 3.5 MeV obtained by Poenitz²⁾ and others are somewhat higher than the present results. The measurements of the prompt γ -rays have been performed with the time-of-flight technique which drastically reduces the influence of secondary low-energy neutrons.

A comparison of the results with the theoretical calculations shows reasonably good agreement. *A priori*, we expect that the compound-nucleus calculations, with the parameters adopted, should yield the correct cross sections below 5–6 MeV to within about 30%. The results for indium are well within this limit while the deviation for gold is somewhat larger at 3–4 MeV. We believe that the deviation is caused by irregularities in the level density of ^{197}Au which governs the strength of competing (n, n') reactions. It is possible that at about 3 MeV there are groups of levels responsible for the shape of the experimental cross section. The first step in the excitation curve for gold occurs at 1–2 MeV. This is due to the excitation of the first few levels via (n, n') channels. The levels are known (and individually included in the calculations) and the step in the curve is rather well reproduced by the model.

Above 5–6 MeV in neutron energy, reactions of direct type may begin to contribute significantly. An estimate of this contribution can be obtained from calculations based on the direct-semidirect model. In order to get a rough estimate for the reaction $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$, we have utilized the results of previous calculations for $^{206}\text{Pb}(n, \gamma)^{207}\text{Pb}$ [ref. ³⁶⁾] and $^{208}\text{Pb}(n, \gamma)^{209}\text{Pb}$ [ref. ³⁷⁾]. These results were applied [in a similar way as in ref. ³⁸⁾] to the Nilsson states³⁹⁾ assuming a deformation parameter $\varepsilon = 0.1$ for ^{198}Au . The results (dashed line in fig. 2) indicate that the DSD contribution is rather low in the energy range considered in this work. The presence of direct reactions also affects the compound-nucleus cross sections. However, a previous study⁴⁰⁾ has shown that this effect is also relatively small.

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GIANT-RESONANCE STUDIES
PAPER III

STUDY OF THE $^{208}\text{Pb}(n, \gamma)^{209}\text{Pb}$ REACTION BETWEEN 0.8 AND 7.7 MeV

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Abstract: The reaction $^{208}\text{Pb}(n, \gamma)^{209}\text{Pb}$ was studied from 0.8 to 7.7 MeV to investigate relative contributions of the compound-nucleus and direct and semidirect processes in this energy range. Compound-nucleus reactions dominate below about 5 MeV and semidirect processes above 6 MeV. The direct-semidirect (DSD) model with a complex particle-vibration coupling describes the experimental data in the giant resonance region. A relatively large imaginary term is necessary to obtain a good fit to the data indicating either that the reactions proceed to a large extent in more complicated ways than the simple two-step semidirect reaction or that the model has a serious defect in its present formulation. A second objective was to search for a possible excitation of the isoscalar E2 and the M1 giant resonances by measuring asymmetries around 90° in the angular distribution of the γ -rays. The results indicate no (or very weak) asymmetry effects.

E NUCLEAR REACTIONS $^{208}\text{Pb}(n, \gamma)$, $E = 0.8\text{--}7.7$ MeV; measured $\sigma(E, \theta)$; compound-nucleus, direct-semidirect model analyses.

1. Introduction

The first measurements¹⁾ of γ -ray spectra from neutron capture in the giant dipole resonance (GDR) energy region were performed on ^{208}Pb . The results gave conclusive evidence for the semidirect reaction mechanism in which an intermediate state is formed consisting of the neutron in a bound single-particle state and the nucleus excited into the giant dipole state. The experimental results for ^{208}Pb have since then often been used for comparison with theoretical calculations based on

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the direct-semidirect (DSD) model²⁻⁵⁾ and the more recently proposed pure-resonance (PR) model⁶⁾. The theoretical work raised several questions and motivated us to extend the previous measurements.

The DSD model with complex particle-vibration coupling³⁾ describes satisfactorily most of the existing experimental data. However, a rather large value of W_1 , the strength of the imaginary part of the symmetry potential, is required to obtain adequate fits to the capture cross sections of heavy nuclei. The dominating contribution to the transition matrix element comes then from the imaginary term of the coupling. This is somewhat difficult to understand within the frame of the DSD model. This objection disappears in the PR model⁶⁾ which yields cross sections much less sensitive to W_1 . The behaviour of the cross section in the low-energy part of the GDR is of crucial importance because a larger contribution of compound nucleus (CN) processes in this region would imply that smaller W_1 values in the DSD model are required to fit the data.

Another interesting question concerns the excitation of other giant resonance modes, e.g. the giant quadrupole (GQR) and magnetic dipole (GMR) resonances, in neutron capture. The isoscalar GQR is located at 10.5 MeV [ref. ⁷⁾] and the isovector at 22.5 MeV [ref. ⁷⁾], i.e. on either side of the GDR at 13.4 MeV. In the presence of strong E1 transitions it may be difficult to observe the effect of the GQR in neutron capture except in the angular distribution of the γ -rays. The interference of E1 and E2 radiation causes a fore-aft asymmetry, the magnitude of which reflects the strength of the GQR. The information on the M1 strength in heavy nuclei is scarce and only fragments of the giant M1 strength have been observed⁸⁾. An E1-M1 interference would also cause a fore-aft asymmetry in the angular distributions.

Theoretical calculations of the angular distributions of $^{208}\text{Pb}(n, \gamma_0)^{209}\text{Pb}$ have been made⁹⁻¹²⁾ with the DSD model to include E2 radiation. The results indicate a rather weak backward peaking around and below the isoscalar GQR at $E_n \sim 6.6$ MeV (corresponding to $E_x \sim 10.5$ MeV) and a much more conspicuous forward peaking at the isovector GQR at $E_n \sim 20$ MeV. Asymmetry measurements, recently made at Los Alamos National Laboratory in the latter energy region¹³⁾, show a strong forward peaking in agreement with the theoretical predictions. The region around the isoscalar GQR is studied in the present experiment.

The 90° differential cross sections of the reaction $^{208}\text{Pb}(n, \gamma_0)^{209}\text{Pb}$ were determined in the neutron energy range from 0.8 MeV to 7.7 MeV. Measurements were also made at 55° and 125° at neutron energies 3.8, 5.9, 6.2 and 7.2 MeV in order to determine the asymmetry factor for comparison with theoretical predictions.

2. Experimental

Measurements were performed with the 4 MeV Van de Graaff accelerator at Bruyères-le-Châtel and the 6 MV tandem accelerator at Uppsala. In both cases

the γ -rays were detected by a large NaI(Tl) scintillation spectrometer. Time-of-flight techniques were used to suppress background and to facilitate background subtraction. Details of the experimental arrangements have been published previously^{14,15}.

The measurements at Bruyères-le-Châtel were made for neutron energies between 0.8 and 5.9 MeV. At the lower energies, neutrons were produced by the $^3\text{H}(p, n)^3\text{He}$ reaction using a solid target of tritium adsorbed in titanium. Above 3.2 MeV, the $^2\text{H}(d, n)^3\text{He}$ reaction was utilized with a gas target; the gas pressure was adjusted to yield a total energy spread over the sample of about 100 keV. The Uppsala measurements, using 5.7 to 7.7 MeV neutrons produced by the $^2\text{H}(d, n)^3\text{He}$ reaction with a gas target, had a neutron-energy spread over the sample of about 150 keV.

The sample consisted in both experiments of 436 g of enriched (98.7%) ^{208}Pb . Due to differences in the experimental conditions the sample was shaped differently in the two experiments. At Bruyères-le-Châtel it was a solid cylinder 3.9 cm in length and 3.5 cm in diameter while at Uppsala it was a hollow cylinder with a length of 5.0 cm and inner and outer diameters of 4.0 and 5.0 cm, respectively. In both cases the sample was placed with the cylindrical axis vertical i.e. perpendicular to the plane defined by the ion beam and the γ -ray detector collimator.

The experiment is difficult because of low (n, γ) yield and high background. The low neutron binding energy of ^{209}Pb , 3.94 MeV, means that the γ -ray spectrum from $^{208}\text{Pb}(n, \gamma)^{209}\text{Pb}$ occurs in the same region as background γ -rays originating from thermal and slow neutron capture in the NaI crystal and surrounding material. The (n, γ_0) yield is particularly difficult to determine around $E_n \sim 3$ MeV because of the $E_\gamma = 6.8$ MeV peak arising from neutron capture in the NaI crystal. However, since the background spectrum has a significant tail extending up to about 9 MeV the signal-to-background ratio is poor also at higher neutron energies.

The (n, γ_0) intensities were determined by unfolding the upper part of the γ -ray spectra by means of known response functions of the spectrometers. The intensities were corrected for neutron and γ -ray attenuation in the sample, for neutron multiple scattering and for neutron source anisotropy over the sample.

3. Results and discussion

The results of the cross-section measurements are shown in fig. 1 together with the results of the early experiment¹). We note that the results agree within errors in the overlapping region between 6 and 8 MeV. The error bars reflect in most cases the uncertainty in the determination of the absolute efficiency of the γ -ray detector. Following the previous representation we display the results in units of the differential cross section at 90° multiplied by 4π even though it causes some complication in comparison with the theoretical calculations. In the earlier work¹) the 90° cross sections (multiplied by 4π) were compared with angle-integrated

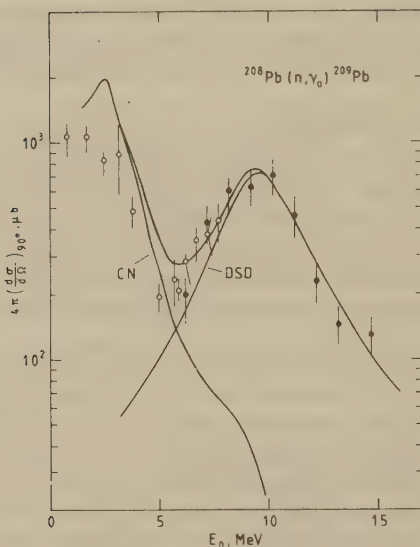


Fig. 1. Experimental cross sections for γ -rays to the $2g_{9/2}$ ground state of ^{209}Pb compared with theoretical calculations from compound-nucleus (CN) and direct-semidirect (DSD) models. The solid points are from ref. ¹⁾ and the open circles from the present experiment.

theoretical cross sections and thus angular distribution effects were ignored. This procedure might be justified in qualitative comparisons of the cross sections but in the present discussion we are concerned with the more detailed shape of the energy dependence of the cross section and angular distribution effects are significant. As discussed below, these effects have been taken into account in the theoretical results shown in fig. 1.

Theoretical cross sections shown in fig. 1 indicate that CN reactions dominate below $E_n \sim 5$ MeV, and that DSD processes are predominant above $E_n \sim 6$ MeV. In the intermediate region, the CN and DSD contributions are roughly equal and interference between the two components might be important ⁵⁾.

In the low energy region, the cross sections calculated from the statistical (Hauser-Feshbach) theory reproduce the observed energy dependence reasonably well but they are a factor of about 1.7 too high. This factor is well within the expected error arising from uncertainties in the level densities and in the γ -ray strength function. The level densities were evaluated from the Gilbert-Cameron formulas ¹⁶⁾ normalized to the observed number of low-lying levels. The transmission coefficients for particle emission were obtained from an optical model calculation using Rosen parameters ¹⁷⁾ and the γ -ray strength was derived from the experimental photo-nuclear cross section ¹⁸⁾. Only E1 transitions were considered in the calculation.

The angular distribution of the γ -rays to the ground state of ^{209}Pb are nearly isotropic in this energy range. Effects due to level width fluctuations are probably important in the lower energy region, where few channels are open, but we have not taken these effects into account.

We conclude that the cross section remaining after subtracting the CN contribution will be a rather symmetric resonance around $E_n \sim 9.5$ MeV. Furthermore, it will have almost the same shape as the GDR cross section observed in photonuclear reactions. Such symmetry cannot be obtained with a real particle-vibration coupling as proposed in the original derivations of the DSD model. With real coupling, the direct and semidirect amplitudes interfere destructively below the GDR peak and constructively above causing marked asymmetry in the DSD cross section. Addition of an imaginary coupling term has the effect of restoring the more symmetric resonance shape.

In the present DSD calculations we adopted the complex coupling form of ref. ³⁾ with the strength values $V_1 = 75$ MeV and $W_1 = 140$ MeV. The real strength, V_1 , was taken to be the same as in previous systematic analyses ⁴⁾ with the DSD model and W_1 was adjusted so that the calculations reproduce the shape and magnitude of the data. The optical model parameters were taken from ref. ¹⁷⁾. The GDR parameters ¹⁸⁾ were: $E_R = 13.42$ MeV, $\Gamma_R = 4.05$ MeV and $\sigma_{-1} = 251$ mb. The $2g_{9/2}$ wave function was calculated using the Woods-Saxon potential and a spin-orbit potential of Thomas type with $r_0 = 1.25$ fm, $a = 0.65$ fm and $(V_{s.o.})_0 = 5.5$ MeV. The real potential depth was adjusted by the computer program to give the experimental binding energy of 3.94 MeV. We have not studied systematically the sensitivity of the DSD calculations to the input parameters. It has previously been noted ¹⁹⁾ that the results are sensitive to assumptions about the optical model parameters. It should also be noted that the magnitude of the semidirect cross section has an uncertainty of nearly 20% merely due to the uncertainty of the observed bremsstrahlung-weighted cross section, $\sigma_{-1} = 251 \pm 20$ mb. But even though the total uncertainty of the DSD results may be rather large, it seems inevitable that the imaginary term dominates as stressed in fig. 2.

Fig. 2 shows the contributing terms in the DSD calculations. With real coupling only (the curve labelled $V_1 = 75$ MeV, $W_1 = 0$ MeV) the cross-section curve is asymmetric – as discussed above. The interference makes it impossible to obtain an adequate fit to the data even when a larger V_1 value is used to renormalize to the observed peak value of the cross section. The imaginary coupling term ($V_1 = 0$ MeV, $W_1 = 140$ MeV) restores the symmetry of the resonance. The relative importance of the terms is the same as observed previously ²⁰⁾ in neutron capture by ^{89}Y and also in this case the dominating contribution comes from the imaginary coupling term. In fact, in both cases this term alone, appropriately renormalized, would give a reasonable description of the data.

While the real part of the coupling corresponds to the two-step reaction, i.e. excitation of GDR and its deexcitation, one may consider the imaginary part to

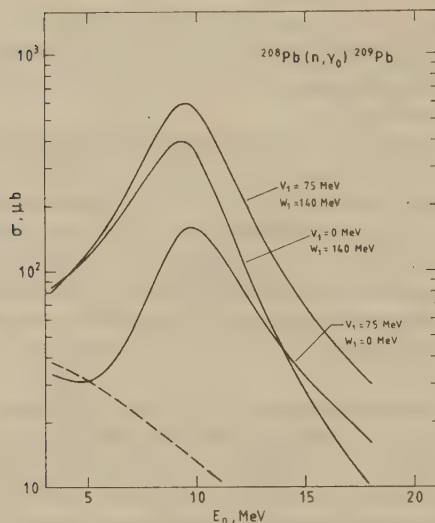


Fig. 2. Theoretical cross sections obtained from the DSD model with various sets of V_1 and W_1 values. The direct cross section is indicated by the dashed line.

account for more complicated modes of exciting the GDR. If this is the correct picture, then it seems appropriate to explore these indirect excitation modes. The question has also been asked whether the imaginary coupling only plays the rôle of covering up a defect of the DSD model. An alternative approach is the pure-resonance (PR) model⁶⁾ in which the non-resonant (direct) term is absent. The imaginary coupling term in this model has a negligible effect. The results⁶⁾ for $^{208}\text{Pb}(n, \gamma_0)^{209}\text{Pb}$ appear to be less asymmetric than the DSD results with the real coupling. However, they do not give nearly as good a description of the data as the DSD calculations with complex coupling.

The inclusion in the DSD model of the isoscalar E2 and the M1 giant resonances has a negligible effect on the cross section. The only observable effect would be in the angular distributions of the γ -rays. The γ -ray spectra were therefore measured at a few selected neutron energies at the angles 55° and 125° in addition to 90° . From the results we obtain the angular distribution coefficients

$$A_1 = \frac{I(55^\circ) - I(125^\circ)}{I(55^\circ) + I(125^\circ)} = \frac{0.57a_1 - 0.02a_2 - 0.39a_3}{1 - 0.39a_4},$$

$$A_2 = 2 - \frac{4I(90^\circ)}{I(55^\circ) + I(125^\circ)} = 2 - \frac{2 - a_2 + 0.67a_4}{1 - 0.39a_4},$$

where $I(\theta)$ is the γ -ray intensity at the angle θ and a_v are the Legendre polynomial

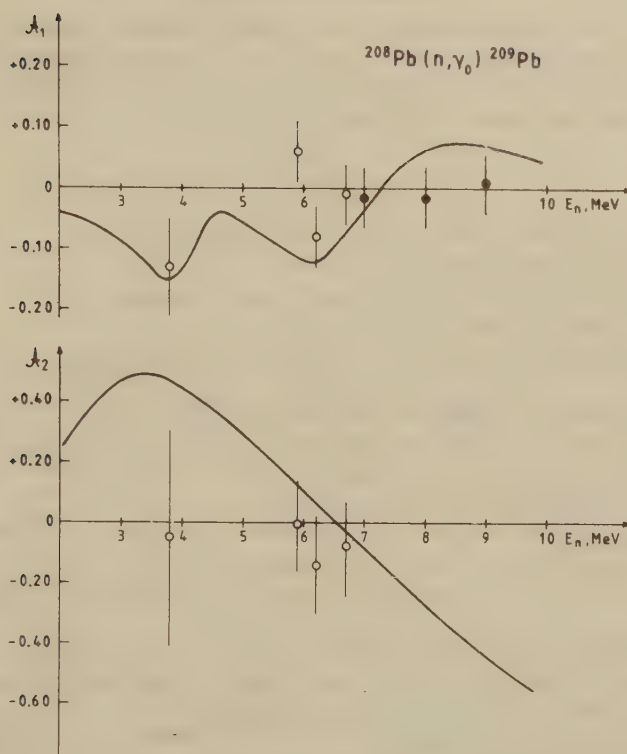


Fig. 3. Energy dependence of the angular distribution coefficients A_1 and A_2 . The solid points are from an experiment ¹³⁾ at Los Alamos National Laboratory and the open circles from the present experiment. The theoretical curves are from ref. ¹⁰⁾.

coefficients. The coefficient A_1 measures the fore-aft asymmetry and A_2 is approximately equal to a_2 for small a_4 values.

The results are compared in fig. 3 with calculations ¹⁰⁾ based on the DSD model including E1, E2 and M1 contributions. The predicted interference effect between radiation of opposite parity is rather small. The dip in the curve for the A_1 coefficient around $E_n \sim 6$ MeV is due to E1-E2 interference and that below $E_n \sim 4$ MeV to E1-M1 interference. The experimental points around 6 MeV indicate that the influence of the isoscalar GQR is even less than expected from the model. The point at 3.8 MeV may indicate a contribution from the M1 resonance. However, it is evident from fig. 1 that CN reactions dominate at this energy and that any asymmetry effect would be masked by this contribution. The observed A_2 values are also close to zero. This is in accord with our calculations for CN reactions (not

shown in fig. 3) and, around 6 MeV, also with the DSD calculations since A_2 changes sign in this energy region. The theoretical curve ¹⁰⁾ is roughly the same as that obtained in a previous DSD calculation ²¹⁾. The latter results were used in obtaining the differential cross sections at 90° given in fig. 1.

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GIANT-RESONANCE STUDIES
PAPER IV

THE GIANT ISOVECTOR E2 RESONANCE IN CALCIUM OBSERVED IN RADIATIVE NEUTRON CAPTURE

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Abstract: The reaction $^{40}\text{Ca}(n, \gamma_0)^{41}\text{Ca}$ has been studied in the neutron energy range 20–28 MeV, where the isovector giant quadrupole resonance is expected. Interference between E1 and E2 radiation gives rise to a fore-aft asymmetry of the emitted γ -rays. The measured asymmetries are compared with calculations based on the direct-semidirect capture model. Good agreement with the experimental data is obtained assuming an isovector E2 resonance located at 32 MeV with a strength exhausting about 35% of the isovector sum rule. This corresponds to the full strength of the T_c component.

NUCLEAR REACTIONS $^{40}\text{Ca}(n, \gamma_0)$, $E = 7\text{--}28$ MeV; measured $\sigma(E; \theta)$; deduced isovector giant quadrupole resonance parameters. Natural target.

1. Introduction

The giant dipole resonance (GDR) in nuclei is known to be strongly excited in nucleon capture reactions. The main features of the reaction mechanism are well described by the direct semidirect (DSD) model. In this model one adds the amplitudes of one-step (direct) and two-step (semidirect) processes. In the latter case, the first step, the excitation of the giant dipole state, is primarily caused by the isospin nucleon nucleus interaction. The form factors used in the early model calculations^{1,2)} were real functions, which resulted in qualitative rather than quantitative agreement with the experimental results. Later analyses with a

complex coupling function^{3,4}) have substantially improved the fit to the experimental data.

In this paper we report on new measurements and DSD calculations on the reaction $^{40}\text{Ca}(n, \gamma_0)^{41}\text{Ca}$. This reaction has previously been studied⁵⁻⁷) in the neutron energy range 3.5–17 MeV. The measurements have been extended up to 28 MeV, first of all to explore the effect of the isovector E2 resonance (IVGQR). Furthermore, the data collected previously⁷) have been re-examined in the light of a better determination of the detector efficiency. The revised cross sections are in better agreement with other results^{5,6}).

The same nucleon-nucleus interaction that excites the GDR should also selectively excite other isovector modes. Higher multipoles are weakly excited in nucleon capture, but DSD calculations predict that significant effects of the isovector giant quadrupole resonance (IVGQR) should be observed in the angular distribution of the γ -rays. In proton capture these effects are obscured by direct (kinematic) effects^{8,9}), so neutron capture reactions are more favourable for these studies. It should be easiest to observe the fore-aft asymmetry caused by interference between E2 and E1 radiation. The first experiment to show this¹⁰) was $^{208}\text{Pb}(n, \gamma_0)^{209}\text{Pb}$. A very strong forward peaking of the γ -rays was observed at neutron energies around 20 MeV. The results correspond to an IVGQR at 22.5 MeV having roughly the full strength of the energy-weighted sum rule (EWSR). These results indicate that neutron capture may provide a means of investigating the properties of the IVGQR, which are difficult to obtain in other reactions.

A review of experimental data on isovector quadrupole resonances¹¹) shows that most of the existing knowledge stems from electron-scattering experiments. The observed excitation energies can be represented by the expression $E_x = EA^{-1}$, where E varies between 135 MeV for large A -values and 120 MeV at $A \approx 60$. The resonance widths range from 5 to 10 MeV and the fraction of the sum rule exhausted by the resonance is of the order of 80%, but depends strongly on the shape (volume or surface) assumed for the interaction. Similar data have been obtained from studies of angular distributions in proton capture¹²). In light nuclei, proton capture and photonuclear work have indicated quadrupole strength spread over wide energy regions.

The experimental results on calcium are compared with new calculations based on the DSD model. There are grounds for new calculations not only because of the extended energy range for which we now have experimental data, but also because of new information^{13,14}) on optical-model parameters from neutron scattering on ^{40}Ca .

2. Experimental arrangement

The experiment was performed with the Uppsala 7 MV tandem accelerator. Neutrons were produced by the reaction $^3\text{H}(d, n)^4\text{He}$ for measurements above 20

MeV and by $^2\text{H(d,n)}^3\text{He}$ for remeasurements of the cross sections between 7 and 14 MeV. In both cases gas target systems were used with 2.5 cm long gas cells. The calcium sample (cylindrical in shape, weighing 573 g) was placed 14 cm from the gas cell with its axis perpendicular to the (horizontal) reaction plane. The γ -ray detector was a NaI(Tl) scintillator, 23 cm in diameter and 21 cm long, placed at a distance of 110 cm from the Ca sample in a heavy shielding of lithium hydride, lead and paraffin. The collimator aperture was plugged with lithium hydride and a shadow bar of hevimet was placed between the collimator and the gas cell. The detector with its shielding was mounted on an arm, which could be rotated around the symmetry axis of the Ca sample.

Time-of-flight techniques were used to reduce neutron-induced background. The accelerator delivered a pulsed deuteron beam with a width of about 3 ns at a frequency of 2 MHz. The overall time resolution of the γ -ray detection system was about 5 ns. The neutron intensity from the target was routinely checked by a time-of-flight plastic scintillator. The neutron flux from the gas target was measured at the beginning and end of each experimental period with the aid of a polyethylene telescope.

In general, most of the uncertainty in the determination of fast neutron capture cross sections is related to the γ -ray detector efficiency. In our previous experiments, the efficiency was estimated from response line shapes measured with the reactions $^{13}\text{C(p,}\gamma)^{14}\text{N}$, $^{11}\text{B(p,}\gamma)^{12}\text{C}$ and $^3\text{H(p,}\gamma)^4\text{He}$ yielding γ -rays in the energy range 10–28 MeV. None of these reactions, however, produced a single monoenergetic γ -ray in the detector. In particular, the line shapes for low pulse heights are masked by soft γ -rays produced by the reaction itself and by reactions in target backings and other material. We assumed that the low-energy tail of the response line had a constant value. Combined with the estimated probability for an incident γ -ray to interact with the crystal ($P \approx 0.95$) and the measured γ -ray attenuation in the material in the collimator aperture, it was possible to use the response line shape to determine the γ -ray peak efficiency (in a 3 MeV region around the full-energy peak). However, we have recently measured the absolute efficiency at 15 MeV employing the reaction $^{10}\text{B}(^3\text{He,p})^{12}\text{C}$ to excite the 1^+ state at 15.1 MeV in ^{12}C . The method¹⁵⁾ consists of detecting the protons in a forward cone and the 15 MeV γ -rays at 55° (or 125°). The efficiency is obtained as the ratio between the $p\gamma$ coincidence rate and the proton singles rate. The new peak efficiency is 11% higher than the previously estimated value. It was used to renormalize our previous estimated efficiency curve and applied to the results presented in this report.

Measurements of the $^{40}\text{Ca(n,}\gamma_0)$ yield were performed at 55° , 90° and 125° with respect to the incident beam. The results were corrected for attenuation of neutrons and γ -rays in the sample and for anisotropy of the neutron flux. The corrections were calculated by means of a new computer program and checked with a Monte Carlo calculation. These calculations were found to give somewhat smaller

corrections than our previous estimates. Hence, the corrections tend to lower the cross-section values given earlier⁷⁾ in the low E_n region.

Several investigations were performed to ascertain that the observed fore-aft asymmetries are real and not due to any shortcomings in the experimental equipment or the measuring procedure. One method of checking that pile-up effects are not much more important at 55° than at 125° is to calculate asymmetries for γ -ray transitions to excited states in ^{41}Ca . These asymmetries are found to be weak compared with the ground-state asymmetry as expected. A further means of investigating possible effects of the experimental procedure on the measured asymmetries is to use the ground-state transition from the 15.11 MeV 1^+ state in ^{12}C , populated by the $^{12}\text{C}(n, n')$ reaction. This experiment also gives a valuable energy calibration point. The results of the $^{12}\text{C}(n, n')$ measurements are consistent with an angular distribution symmetric around 90° , as is expected.

3. Theoretical calculations

The calculations of cross sections have been made using the theory of ref.²⁾ modified to explicitly include direct capture. The transition amplitude can be written as

$$T_L = \langle \Psi_{nlj} | d_L(r) | \chi^{(+)} \rangle + \left\langle \Psi_{nlj} \left| \frac{h_L(r)}{E_\gamma - E_R + \frac{1}{2}i\Gamma_R} \right| \chi^{(+)} \right\rangle, \quad (1)$$

where $\chi^{(+)}$ is the wave function of the scattering state and Ψ_{nlj} is the final single-particle state. The first term represents the direct amplitude, where $d_L(r)$ is the single-particle multipole operator. The second term is the semidirect amplitude, which accounts for the excitation of the giant-resonance state with energy E_R and width Γ_R . The interaction between the incident nucleon and the nucleus is contained in the coupling $h_L(r)$. Complex form factors^{3,4)} were used to describe this interaction. For isovector transitions, both dipole ($L = 1$) and quadrupole ($L = 2$), form factors of the type

$$h_L(r) \propto r^L \left[V_L f_r(r) - iW_L b \frac{df_i(r)}{dr} \right] \quad (2)$$

were used, where V_L and W_L are the depths of the real and imaginary parts of the symmetry potential and $f_r(r)$ and $f_i(r)$ are the real and imaginary Woods-Saxon form factors.

The proportionality factor includes the strength of the giant resonance state in terms of the EWSR. In the case of ^{41}Ca , $T_0 = \frac{1}{2}$ and the isovector giant resonance states are split into two components $T_< = \frac{1}{2}$ and $T_> = \frac{3}{2}$. Conservation of isospin in direct capture requires that only the $T_<$ component be excited. Estimates of the energy splitting of the GDR were taken from ref.¹⁶⁾:

$$E_> - E_< = (T_0 + 1)\bar{V}_1/A, \quad (3)$$

where $\tilde{V}_1 \approx 60$ MeV. The fractional strength distribution¹⁷⁾ is given by

$$\frac{S_>}{S_<} = \frac{1}{T_0} \frac{1 - 1.5T_0/A^{2/3}}{1 + 1.5/A^{2/3}} \quad (4)$$

Similar expressions can be derived for the quadrupole resonance¹⁸⁾ and, in particular,

$$\frac{S_>}{S_<} = \frac{1}{T_0} \frac{1 - 2T_0/A}{1 + 2/A} \quad (5)$$

It can be seen that the $T_>$ state of ^{41}Ca is expected to carry more strength than the $T_<$ state, in contrast to the situation in most other cases (with $T_0 \geq 1$). The ratios defined in eqs. (4) and (5) are 1.7 and 1.9, respectively.

For isoscalar quadrupole transitions the same surface-peaked form factor was used as in ref.⁶⁾:

$$h_2(r) \propto r \frac{d}{dr} \left[V_0 f_i(r) + iW_0 4b \frac{df_i(r)}{dr} \right] \quad (6)$$

The strengths of the potentials V_0 , W_0 were taken to be $V_0 = -50$ MeV, $W_0 = 10$ MeV, which are close to optical-model values.

In this report we present calculations performed with optical-model parameters from a recent neutron elastic-scattering experiment¹¹⁾ on calcium. The 90° cross sections and angular distributions were computed for γ -ray transitions to the $1f_7$ ground state ($S = 0.86$) of ^{41}Ca . The potential strengths V_1 and W_1 were treated as free parameters and it was found that $V_1 = 120$ MeV and $W_1 = 40$ MeV gave a reasonably good description of the experimental data. It was assumed that the $T_<$ component of the GDR, located at $E_R = 18.1$ MeV, has a width $\Gamma_R = 4.0$ MeV and exhausts 38% of the EWSR, i.e. all of the estimated $T_<$ component. The $T_>$ resonance should not be excited but, in order to fit the data we located another GDR component at the position of the $T_>$ component, $E_R = 20.6$ MeV, with a width of 4.0 MeV and a strength of 12% of the EWSR corresponding to 20% of the estimated $T_>$ component.

The energy and width of the ISGQR were taken to be 18.4 MeV and 4.2 MeV, respectively, and the strength was assumed to be 60% of the EWSR. The $T_<$ part of the IVGQR was tentatively located at $E_R = 32$ MeV: the width was taken to be 5 MeV and the strength 35% of the EWSR, which corresponds to the full strength of the $T_<$ component.

Compound-nucleus reactions dominate in the neutron-energy region below the GDR. The results of statistical-model calculations outlined in ref.⁷⁾ are also included for comparison with the experimental data.

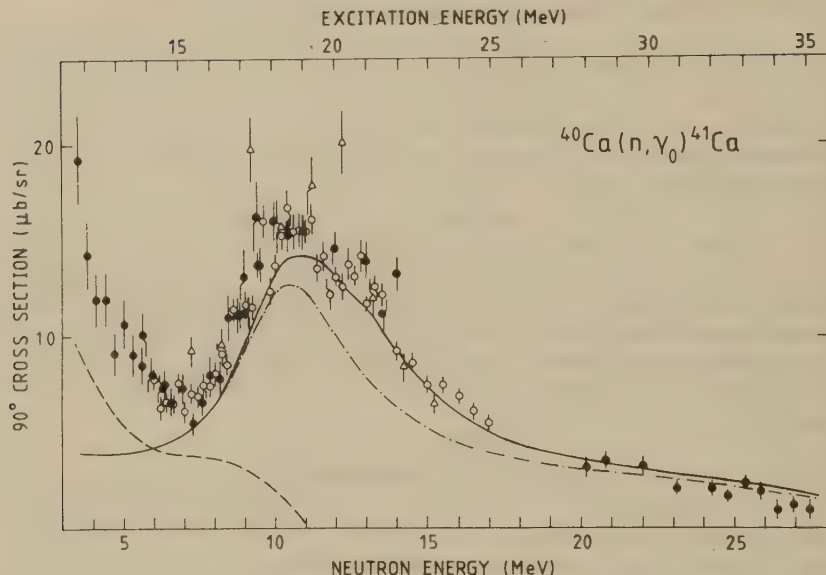


Fig. 1. The 90° cross section of the $^{40}\text{Ca}(n, \gamma_0)^{41}\text{Ca}$ reaction. The experimental data are from ref. ⁵) (open triangles), ref. ⁶) (open circles), ref. ⁷) and the present experiment (full circles). The full and dot-dashed curves represent cross sections calculated on the basis of the DSD model as described in the text. The dashed curve is the compound-nucleus cross section calculated according to the procedure outlined in ref. ⁷).

4. Results and discussion

The primary aim of this experiment is to study angular asymmetries of γ -rays for the reaction $^{40}\text{Ca}(n, \gamma_0)^{41}\text{Ca}$ in the energy region, where the strength of the IVGQR is expected to be localized, i.e. in the excitation energy range 30–35 MeV. The interference between E2 and the dominant E1 transitions should cause a significant fore aft asymmetry. The results were analyzed by means of the DSD model described in the preceding section. It is important to first find out whether the model is capable of reproducing the E1 amplitude correctly. Fortunately, the experimental situation in the $^{40}\text{Ca}(n, \gamma_0)^{41}\text{Ca}$ reaction is quite satisfactory with differential 90° cross sections determined over a wide energy range as well as measurements of angular distributions and analyzing powers in the GDR region.

The 90° cross sections are shown in fig. 1. By comparison with the results of model calculations one may conclude that compound-nucleus reactions dominate in the low- E_n region, below about 5 MeV, and that above $E_n \approx 7$ MeV the predominant reactions are direct and semidirect. In the intermediate region, the

contributions of CN and DSD reactions are about the same and interference effects may be important. The sum of these contributions, ignoring interference effects, tends to give somewhat too high a cross section on the low-energy side of the GDR.

The DSD cross section was first computed assuming for the GDR that only the T_z component can be excited. (See the dot-dashed curve in fig. 1.) This gives, however, a rather poor fit to the data on the high-energy side of the GDR. The data seem to indicate the presence of another GDR component positioned near the expected $T_{\pm}$ resonance energy. DSD calculations were therefore performed tentatively including a resonance with a strength corresponding to 12% of the EWSR (i.e. 20% of the estimated $T_{\pm}$ strength). The origin of this apparent violation of isospin conservation is not presently understood and will be the subject of further studies. The results of the cross-section calculations (solid curve) give quite a good description of the experimental 90° cross sections. Angular distributions and

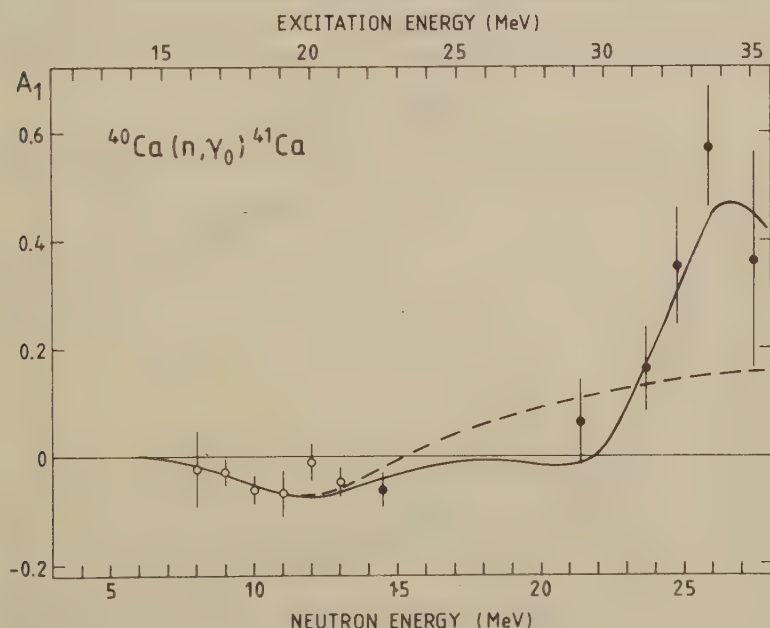


Fig. 2. The fore-aft asymmetry (eq. (7)) of the $^{40}\text{Ca}(n, \gamma_0)^{41}\text{Ca}$ reaction. The experimental data are from ref. 6) (open circles) and from the present experiment (full circles). The full curve is calculated on the basis of the DSD model including an isovector giant quadrupole resonance (IVGQR) with parameters specified in the text. The dashed curve represents the case where no IVGQR was included in the calculation.

analyzing powers have also been computed and excellent agreement with experimental data⁶⁾ was obtained.

Effects of the giant quadrupole resonances on the 90° yield curve are hardly noticeable. These effects are, however, easily observed in the γ -ray angular distributions. The distributions become asymmetric around 90° because of interference between radiation of opposite parity. The fore-aft asymmetry, A_1 , defined as

$$A_1 = \frac{I(55^\circ) - I(125^\circ)}{I(55^\circ) + I(125^\circ)}, \quad (7)$$

has been measured. Here, $I(\theta)$ is the γ -ray intensity at angle θ with respect to the neutron beam. The experimental results for A_1 are compared with the DSD model calculations in fig. 2.

The observed negative values of A_1 around $E_n \approx 12$ MeV reflect the presence of the ISGQR ($E = 18.4$ MeV, $\Gamma = 4$ MeV). The strength of this resonance has been reported from various experiments to be around 60% of the EWSR^{19,20)}. This strength value was used in the present calculations and we confirm the agreement between theory and experiment observed previously⁶⁾. Together with the isoscalar strength

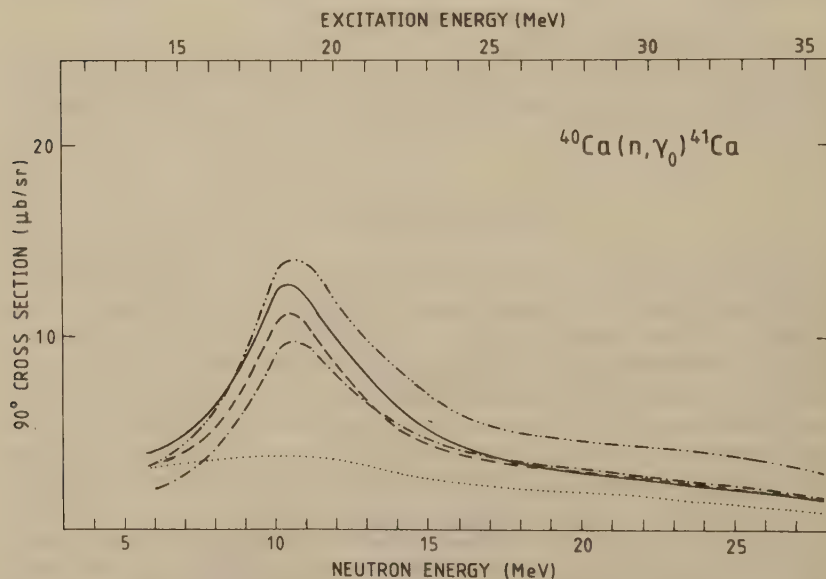


Fig. 3. Cross sections calculated from the DSD model using various optical-model potentials: double-dot-dashed curve, ref. ²¹⁾; full curve, ref. ¹³⁾; dashed curve, ref. ¹⁴⁾; dot-dashed curve, ref. ²²⁾. The dotted curve represents the direct capture cross sections.

contained in the low-lying 2^+ state the ISGQR exhausts the EWSR of isoscalar E2 strength^{19,20}).

The large positive A_1 values above $E_n \approx 20$ MeV are interpreted as being caused by the IVGQR. This interpretation is supported by the DSD model calculations, in which the resonance energy and width were taken to be 32 MeV and 5 MeV, respectively, in approximate agreement with the trends observed for heavier nuclei. The fraction of the isovector EWSR, exhausted by this resonance, was taken to be 35%, which is the full T_- resonance strength according to eq. (5).

To investigate how sensitive the calculated asymmetries are to the optical-model parameters, four different parameter sets were used. Two of these sets are the well-known global sets of Rosen²¹) and Becchetti-Greenlees²²). The other two were obtained from analysis of elastic scattering of neutrons by ^{40}Ca and are therefore more suitable in our study^{13,14}). Fig. 3 shows the variation in the 90° cross section obtained by changing only the optical-model parameter set. The curves for the Becchetti-Greenlees, Rapaport and Tornow parameters are reasonably close to each other, in particular in the region of the IVGQR. The Rosen parameter set is obtained from low-energy data and is not expected to be applicable at higher

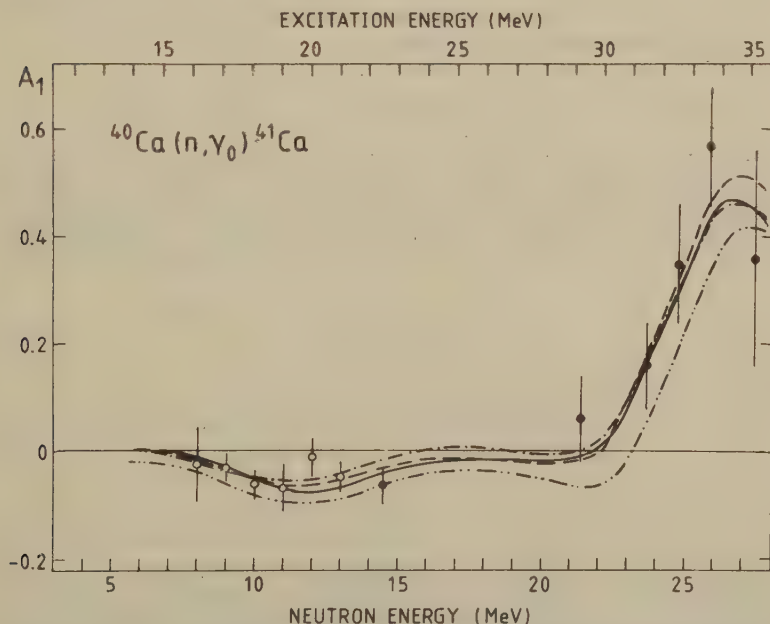


Fig. 4. Fore-aft asymmetries calculated from the DSD model using various optical-model potentials. The same notation as in fig. 3 is used.

energies. Similar conclusions regarding the insensitivity to the optical-model potential can be drawn for the asymmetry (fig. 4).

It is interesting to investigate to what extent the derived resonance parameters depend on the DSD model. This investigation is relatively straightforward, because the E1 amplitude is essentially constant in the IVGQR region and the direct E2 amplitude is negligibly small. Hence, the interference is determined by a constant E1 and a resonant E2 amplitude. The formal treatment of this interference is given in appendix A.

From the derivation in appendix A we find that the phase angle between the E1 and E2 amplitudes is about 60° . The resonance energy is then 32.5 ± 1.5 MeV and the width 6.0 ± 1.5 MeV. These values are consistent with those used in the DSD calculations, 32 MeV and 5 MeV, respectively. One cannot, however, determine the strength in a model-independent way. Using the results from the DSD calculations one finds $S/\Gamma \approx 7\% \times \text{EWSR MeV}^{-1}$. A width of 6.0 ± 1.5 MeV, gives $(40 \pm 10)\%$ of the EWSR.

The present results are the first to show isovector E2 strength concentrated in a resonance in a nucleus as light as calcium. The results are similar to those previously observed in the $^{208}\text{Pb}(n, \gamma)^{209}\text{Pb}$ reaction and demonstrate that the neutron capture reaction is a worthwhile complement to other methods in studying isovector quadrupole resonances in nuclei.

Appendix A

In the region of the IVGQR the E1 amplitude is almost purely direct and can, to a good approximation, be assumed to be independent of energy. The direct E2 amplitude, on the other hand, is very weak in neutron capture, implying that the E2 amplitude can be regarded as purely resonant. Then the A_1 coefficient can be written

$$A_1 \propto \text{Im} \frac{DQ^*}{|D|^2}, \quad (\text{A.1})$$

$$A_1 = \frac{CS}{\Gamma_q} \frac{\cos \Delta + \xi \sin \Delta}{\xi^2 + 1}, \quad \xi = \frac{E_\gamma - E_q}{\frac{1}{2}\Gamma_q}, \quad (\text{A.2})$$

where D and Q are the dipole and quadrupole amplitudes, respectively. The phase angle between them is denoted by Δ and the fraction of isovector quadrupole EWSR by S . The constant of proportionality C and the phase angle Δ are, in this approximation, energy independent, but different for different final states of the residual nucleus. The energy dependence of the A_1 coefficient is shown in fig. A1 in terms of the normalized energy ξ for four phase angles Δ . One can judge from these graphs that for $^{40}\text{Ca}(n, \gamma_0)^{41}\text{Ca}$ the phase angle is close to 60° .

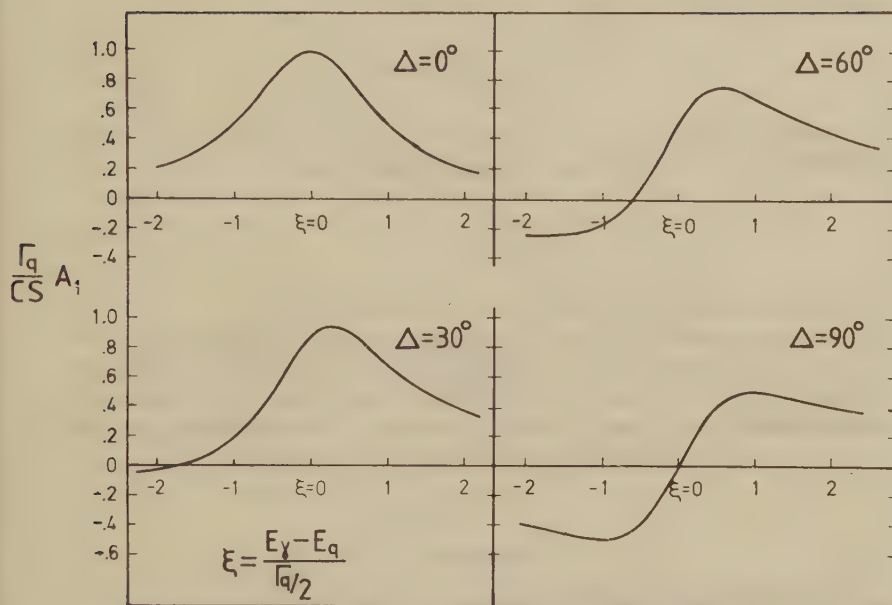


Fig. A1. The energy dependence of the fore-aft asymmetry in the region of the isovector giant quadrupole resonance for different phase angles between the E1 and E2 amplitudes.

We can now easily see to what extent we can rely on our results from the DSD calculations. First of all, the explicit energy dependence of the quadrupole amplitude is supposed to be of the form

$$Q \propto \frac{1}{E_\gamma - E_q + \frac{1}{2}i\Gamma_q}, \quad (\text{A.3})$$

which follows from the DSD model with constant radial matrix elements. The fraction of the isovector quadrupole EWSR exhausted by the resonance is proportional to the full swing of the A_1 coefficient:

$$\delta A_1 \equiv (A_1)_{\max} = \frac{CS}{\Gamma_q}. \quad (\text{A.4})$$

Because the constant C is a model-dependent quantity, we cannot extract the resonance strength from the experiment without utilizing the model. The extraction of the width of the resonance Γ_q and its position E_q from the experimental data depends on the phase angle Δ . The width can, however, be estimated quite

accurately from the rise of the A_1 curve, because

$$\frac{1.3}{\Gamma_q} \leq \left| \frac{1}{\delta A_1} \frac{dA_1}{dE_\gamma} \right|_{\max} \leq \frac{2}{\Gamma_q}. \quad (\text{A.5})$$

The upper limit holds for $\Delta = 90^\circ$ and the lower for $\Delta = 0^\circ$. As a reasonable estimate we may use the average of the two limiting values:

$$\left| \frac{1}{\delta A_1} \frac{dA_1}{dE_\gamma} \right|_{\max} \approx \frac{1.6}{\Gamma_q}. \quad (\text{A.6})$$

The estimate from eq. (A.6) should be correct to within 20%.

The energy of the resonance lies between the points of the maximum rise of the A_1 curve and its maximum. Taking the resonance energy to be equal to the average of these two values, the error is never larger than $\frac{1}{4}\Gamma_q$. From precise measurements of the A_1 curve, the phase angle can be deduced accurately and the width and position of the isovector quadrupole resonance determined.

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GIANT-RESONANCE STUDIES
PAPER V

**A STUDY OF THE ISOVECTOR E2 RESONANCE
IN YTTRIUM**

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ABSTRACT

Gamma-ray spectra from the reaction $^{89}\text{Y}(n,\gamma)^{90}\text{Y}$ were collected at the angles 55, 90 and 125 degrees with respect to the beam in the neutron energy region between 11.8 and 27.0 MeV to study the isovector giant quadrupole resonance (IVGQR) in ^{90}Y .

We observe fore-aft asymmetries in the angular distributions of γ rays. Below $E_n=14$ MeV the asymmetry is weak but rises steeply at about $E_n=18$ MeV for transitions to the $2d_{5/2}$ ground-state doublet of ^{90}Y . The asymmetries are attributed to the interference between γ rays from the isovector E2 state and E1 radiation.

The observed asymmetries, interpreted in the framework of the direct semidirect (DSD) model, show that the isovector E2 resonance is located at an excitation energy of 26.0 ± 1.0 MeV. The data are consistent with a resonance width $\Gamma=10 \pm 2$ MeV and an exhaustion of the fraction of the energy-weighted sum rule (EWSR) available for the T_{-} component.

1. INTRODUCTION

The existence of a giant quadrupole resonance of isovector nature has been indicated by several experiments. Nevertheless, it is difficult to provide accurate information on the parameters of the IVGQR chiefly because its strength is spread over a wide energy region and it is positioned high in the nuclear continuum. The difficulties are particularly serious for light nuclei but persist, to a certain extent, also for medium-mass and heavy nuclei. The conclusions of several review articles on this subject [Pi79], [Ni84] point to the necessity of extending the experiments to other nuclei and also to the need to study the IVGQR by diversified means.

Most of the available information on the isovector E2 has been provided by inelastic electron scattering experiments [Pi79]. The isovector modes are weakly (or not at all) excited in inelastic hadron scattering [Sp81] and in recent experiments using charge-exchange reactions the IVGQR was not revealed [Ta84], [Er84]. The difficulties in using these types of probes are related mainly to the large continuum background on which the resonance is superimposed but also to the overlapping of different resonances. In (e,e') reactions the background can be calculated but it is generally several times larger than the signal [Pi77]. In charge-exchange reactions the shape and strength of the continuum-background contribution are not known in detail.

Experimental and theoretical development has shown that neutron and proton radiative capture reactions, in addition to (γ, N) reactions, constitute valuable complementary tools for studying the IVGQR in nuclei. The intercomparison of neutron- and proton-capture data is important in the sense that neutron capture selects only the $T_{<}$ component of the resonance whereas both $T_{<}$ and $T_{>}$ components are accessible in proton capture. Moreover, both of these reactions can be described by the same macroscopic models - the DSD model and the pure resonance (PR) model.

The giant dipole resonance (GDR) region has been extensively studied through nucleon-capture reactions in the whole mass range. In this energy region, the 90° differential cross sections are sufficiently high (10-100 $\mu\text{b/sr}$) to provide a clear signature of the collective E1 excitation and the data are generally in good agreement with the results of DSD model calculations (see for example [Lin80]). In contrast, the IVGQR is weakly excited in nucleon capture; its presence in the excitation function being completely masked by the high-energy tail of the GDR and direct E1 radiation. Despite this, the IVGQR can be revealed by the effect of interference between γ rays from the isovector E2 state and those from transitions of opposite parity. The effect shows up as a strong forward peaking of the γ -ray angular distributions. The interference terms, i.e. the extent to which odd polynomials appear in the Legendre polynomial expansion, are most easily studied in the asymmetry of γ rays around 90° with respect to the beam.

The fore-aft asymmetry only provides information on the presence of radiation of both parities. In the energy region where the IVGQR is expected, dipole decay predominates and the presence of non-resonant quadrupole and higher amplitudes can be neglected in neutron capture. The presence of other resonant multipoles can not be ruled out *a priori* and will be discussed later.

The reaction $^{208}\text{Pb}(n,\gamma)^{209}\text{Pb}$ was used in the first neutron-capture experiment aimed at the study of the IVGQR via the angular distribution of γ rays [Dr81]. This experiment was not extended beyond an excitation energy of 24 MeV. As a consequence the strength and width of the resonance could not be extracted from the data. Its location at $E_x \approx 22$ MeV was however established within 5% of the value $130A^{-1/3}$ predicted by model calculations [Su73] and in accordance with the systematics for heavy nuclei [Pi79]. The results also show qualitative agreement with asymmetry values calculated using the DSD model [Lo78].

In a previous experiment we studied the IVGQR built on the ground state of ^{41}Ca using the reaction $^{40}\text{Ca}(n, \gamma_0)^{41}\text{Ca}$ and compared the experimental data with DSD model calculations [Ber84]. The results show a resonance located at 32.5 ± 1.5 MeV. The resonance has a width of 6.0 ± 1.5 MeV and exhausts about 35% of the isovector E2 sum rule which corresponds to the full strength of the $T_<$ component.

As far as we know only a few experiments have been performed to study the isovector E2 resonance in nuclei with mass numbers around 90. In an experiment performed some years ago the IVGQR was localized as a broad structure around $E_x = 28$ MeV in the spectrum of electrons scattered inelastically from ^{90}Zr [Fu72]. Later, these authors repeated the experiment and reported a resonance located at $E_x = 26$ MeV, with a width $\Gamma = 7$ MeV and exhausting 73% of the EWSR [Fu76].

In another inelastic electron scattering experiment the IVGQR was localized in ^{89}Y at an excitation energy of 28 MeV [Pi77]. A lower limit of 7 MeV was given for the width of the resonance. With this width the resonance exhausts around 50% of the EWSR. A width of 10 MeV, which is also compatible with the data, implies an exhaustion of about 80% of the EWSR.

In a proton-capture experiment on ^{89}Y [Di77], γ -ray asymmetry data were compared with DSD model calculations using the resonance parameters of ref. [Fu76]. The calculations did not fit the experimental data unless the IVGQR was included. The fraction of the EWSR which provided the best fit to the data was 73% or 40% depending on whether the type of particle-vibration coupling assumed for the interaction was real or complex.

Here we report the results of an experiment using the reaction $^{89}\text{Y}(n, \gamma)^{90}\text{Y}$ to study the IVGQR in ^{90}Y . We also compare the experimental data with calculations based on the DSD model.

In section 2 the experimental arrangement and procedure are described. These depart from those used in our previous experiments mainly in that a new NaI detector has been installed in our γ -ray spectrometer. In section 3 the DSD model formalism is presented which is essential in discussing the parameters used in the calculations. Section 4 deals with the analysis and corrections of the data. In section 5 the results are presented and compared with DSD model calculations.

2. EXPERIMENTAL ARRANGEMENT AND PROCEDURE

2.1 General

The experiment was performed at the Tandem Accelerator Laboratory in Uppsala. Spectra of γ rays following neutron capture in ^{89}Y were recorded at 55° and 125° with respect to the beam for seven neutron energies between 11.8 and 27.0 MeV. For some of the energies spectra were also recorded at 90° . A time-of-flight monitor was used to normalize the runs at different angles. The time-of-flight technique was also used to separate neutron from γ radiation reaching the γ -ray spectrometer.

Monoenergetic neutrons were produced by the $^3\text{H}(d,n)^4\text{He}$ reaction except at the neutron energies 11.8 and 13.7 MeV, for which the $^2\text{H}(d,n)^3\text{He}$ reaction was used. The ion beam was pulsed at 2 MHz and bunched to approximately 3 ns. It was focused onto 2.5 cm long gas cells containing tritium or deuterium at a pressure of roughly $1.5 \cdot 10^5$ Pa. The entrance windows of the gas cells were 4.2 mg/cm^2 molybdenum foils. At the neutron energies 18.5 and 24.2 MeV the thickness of the foil was increased to 25.4 mg/cm^2 . The increase in foil thickness was motivated by the measurement at 18.5 MeV. Without increasing the foil thickness the accelerator potential would have to be too low to provide satisfactory focusing and beam pulsing conditions. The beam current was kept roughly constant at each energy but varied between 0.5 and 1 μA during the whole experiment.

The sample was a metallic yttrium cylinder 6 cm in diameter and 8 cm in length. It was placed with its symmetry axis perpendicular to the reaction plane at a distance of 10 and 11 cm from the beam stop of the tritium and deuterium gas cells, respectively. The neutron energy spread over the sample varied, between 200 and 300 keV (FWHM), depending on the energy.

A hevimet (90% tungsten) shadow bar was placed between the gas cell and the γ -ray spectrometer to reduce the direct neutron irradiation. Neutrons scattered by the sample towards the spectrometer were attenuated by a 40 cm long bar of lithium hydride (LiH) placed in the collimator hole (14 cm in diameter).

2.2 The γ -ray spectrometer

The γ -ray spectrometer consists of a central NaI(Tl) crystal and two plastic scintillators. The latter cover the front and curved surfaces of the NaI crystal and are used in anti-coincidence with it to suppress cosmic-ray background and events with only partial energy deposition. The whole spectrometer is shielded by paraffin, lead and lithium hydride. The spectrometer is mounted on a carriage which can be rotated around the sample and moved radially. The distance between the sample and the NaI detector was 1.1 m. Further details of the spectrometer assembly with the old detector can be found elsewhere [Zo84].

The NaI(Tl) crystal, manufactured by Bicron Inc., was used for the first time in the present experiment. It is a cylinder, 25 cm in diameter and 36 cm in length, viewed by seven photo-multiplier (PM) tubes equipped with active bases for gain stabilization. This type of base has been used at Brookhaven National Laboratory and is described in ref. [Sa84]. Operated in anti-coincidence mode with the plastic scintillator shield the NaI detector has a resolution of 1.5% (FWHM) and 7.2% at one tenth maximum (FWTM) for $E_{\gamma}=22.6$ MeV. These values were

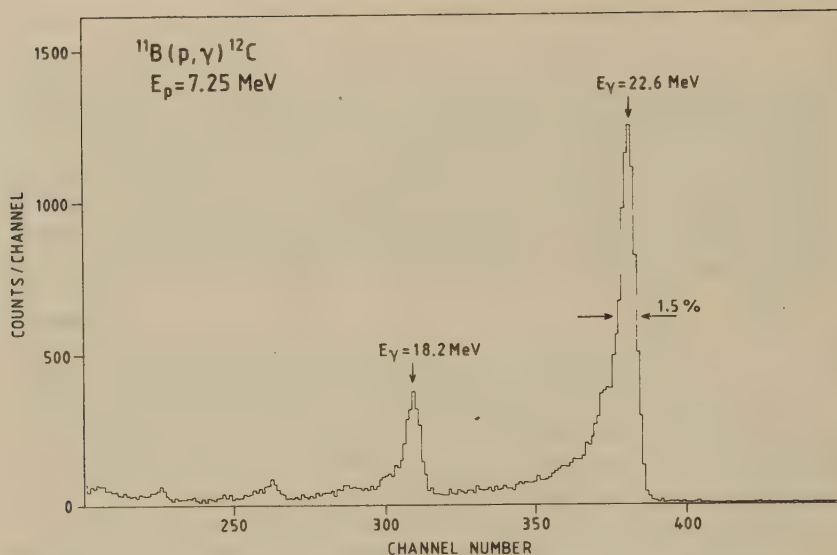


Fig. 1- Response line of the NaI(Tl) detector obtained at $E_Y=22.6$ MeV. The resolution at one tenth maximum (FWTM) is 7.2%.

obtained using the $^{11}\text{B}(\text{p},\gamma)^{12}\text{C}$ reaction at $E_p=7.25$ MeV (see fig. 1). In the present experiment the resolution was worsened by the neutron energy spread over the sample and the LiH in the collimator hole (2-4% FWHM). The detector is equipped with fibre-optic light-guides leading to the window of each photomultiplier tube. The light-guides were used to send short light bursts from a green light-emitting diode (LED) to the PM-tubes.

2.3 The data acquisition system

A schematic drawing of the electronic circuit is shown in fig. 2. The pulses arriving at ADC's 1 to 4 are stored, event by event, on the disc of a PDP 11/40 computer in a 4-parameter set-up. The start of an event is defined by the first ADC to fire. Pulses at the other ADC's are considered as belonging to the event if they arrive within 5 μs of the start. In the following we call the physical gates in fig. 2 hard gates; by soft gates we mean the channel intervals in the different

It is worth noting that with the present arrangement only low-high pile-up is rejected. Through joint action of the NOT and AND2 units, pulses whose amplitudes lie between 0.5 and 10 MeV are selected. This range is our definition of "low pulse" meaning that we accept the pile-up of low pulses which in principle may result in counts in the upper part of the spectrum. In practice, however, the count rate was very low (a few thousand per second) above γ rays from slow-neutron capture in ^{127}I , i.e. above 7 MeV, and in all cases the total count rate up to 10 MeV was kept well below 10^5 per second.

In ADC 2 the linear spectrum of the NaI detector is acquired by relaxing the anti-coincidence condition in the shield. The pulses to the LED are also registered in ADC 4 to provide, together with a scaler, the dead-time correction. The time-of-flight spectrum is registered in ADC 3. The start of the TAC is provided by pulses in the centre detector above 0.5 MeV and the stop by the delayed pulses from the beam pick-up tube located 1 m from the gas cell.

2.4 Procedure

Time-of-flight spectra are shown in fig. 3. These spectra are gated with pulse heights in the NaI detector corresponding to γ rays between the capturing state and states up to an excitation energy of about 5.5 MeV in ^{90}Y . The accepted spectrum (ADC 1) is extracted with a gate on the γ -ray peak in fig. 3. The random background is extracted by a wide gate to the right of the peak. The beam-correlated background was studied in runs without sample, in runs with a carbon sample and, at some energies, also in runs with a bismuth sample. The neutron-separation energy in ^{90}Y is 6.86 MeV while in ^{13}C and ^{210}Bi it is 4.95 and 4.60 MeV, respectively.

The data at each angle were collected in short partial runs lasting from 1 to 5 hours depending on the neutron energy.

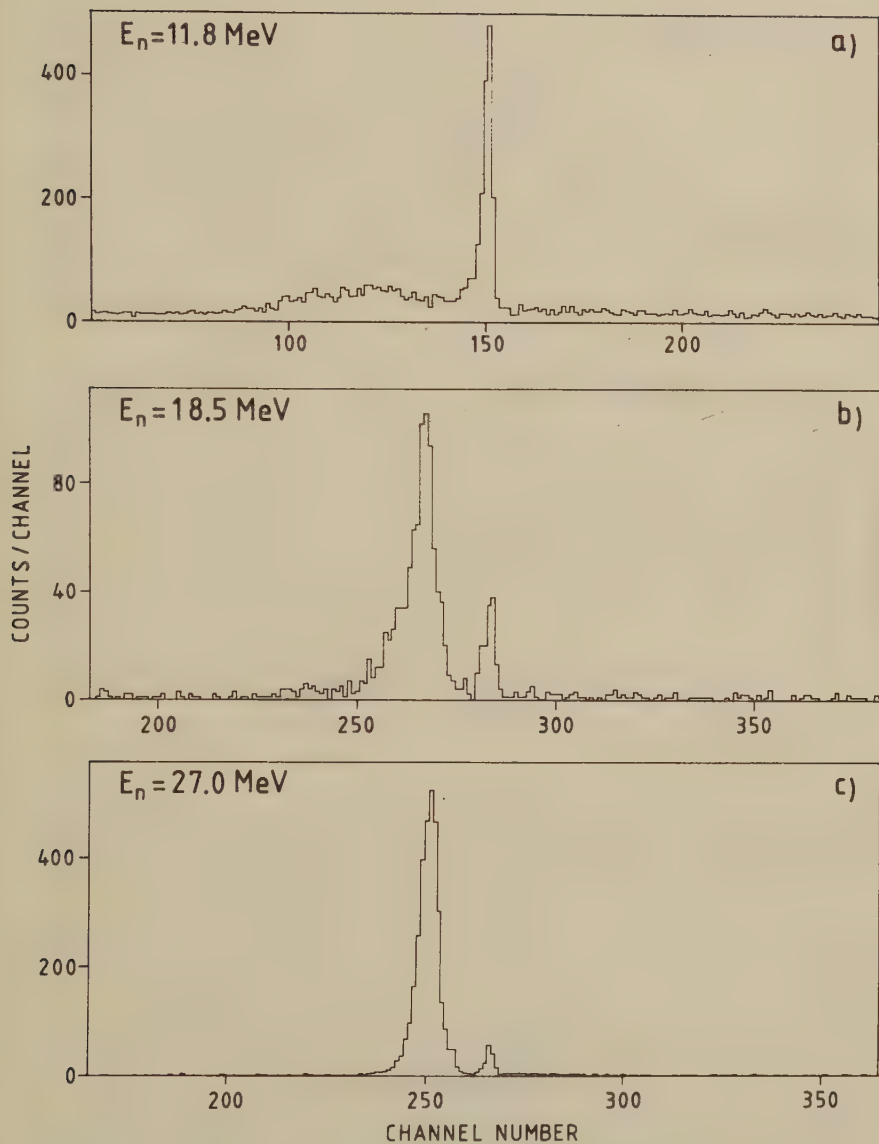


Fig. 3- Time-of-flight sample spectra for the $^{89}\text{Y}(n, \gamma)^{89}\text{Y}$ reaction. The spectra are gated with pulse heights corresponding to γ -ray transitions to states below 5.5 MeV in ^{89}Y . The peaks to the right correspond to γ rays and those to the left to neutrons reaching the NaI detector.

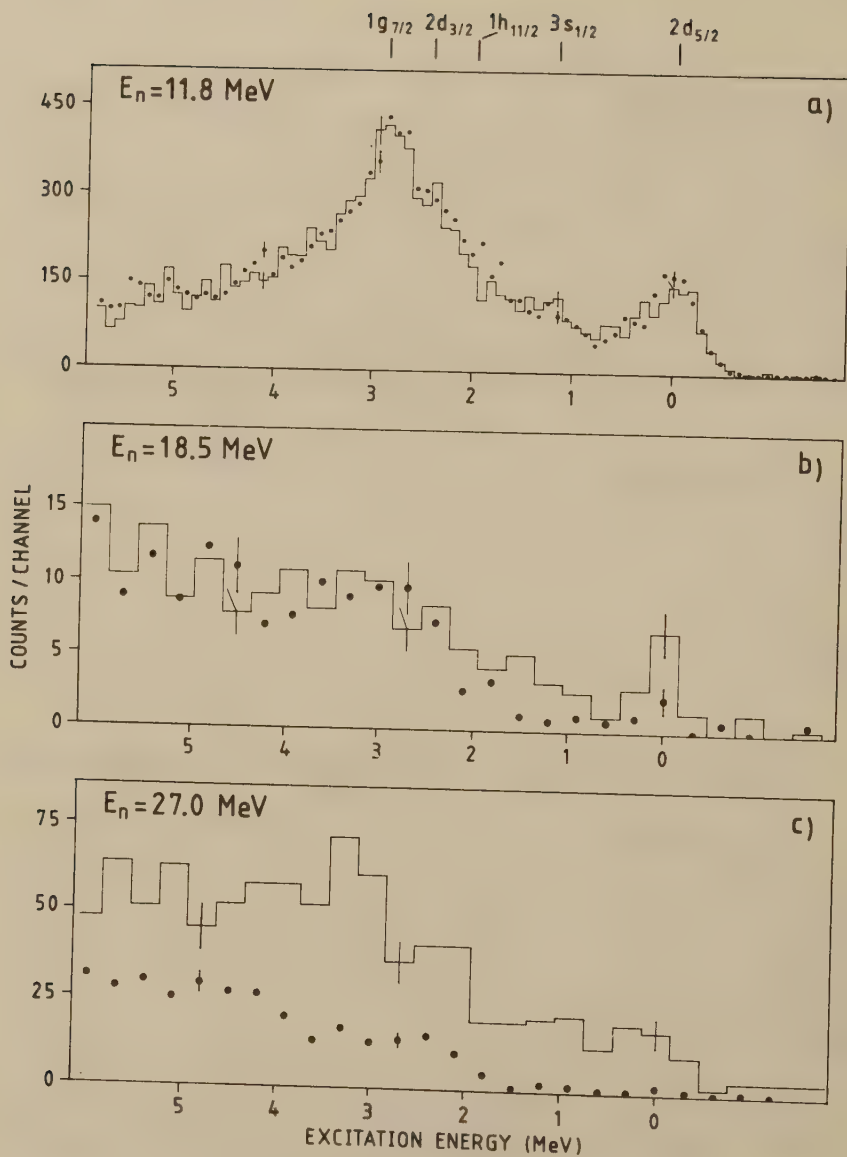


Fig. 4- Accepted γ -ray spectra for the reaction $^{89}\text{Y}(n, \gamma)^{90}\text{Y}$. The histograms represent the 55° and the dots the 125° spectra, respectively. The spectra in b) and c) have been averaged over 3 channels.

Between the partial yttrium runs a carbon sample, and sometimes also a calcium sample, were irradiated. The 15.11 MeV γ -ray transition following the reaction $^{12}\text{C}(n,n')^{12}\text{C}$ was used to ensure that the measured asymmetries were not due to geometrical or other shortcomings of the experimental set-up. The decay of the 15.11 MeV level of ^{12}C ($1^+ \rightarrow 0^+$) is a pure M1 transition and hence symmetric around 90° . An asymmetry consistent with zero was obtained for all carbon runs at each energy. The 15.11 MeV γ line was also used, together with γ rays from the reaction $^{40}\text{Ca}(n,\gamma_0)^{41}\text{Ca}$, for energy calibration.

We observed slow gain shifts despite the active PM-base stabilization. In addition, the system showed a slight non-linearity which is difficult to explain and will be, together with the origin of the gain shifts, subject to detailed studies. The calibration points were well fitted by a second-degree polynomial with $a_2/a_1 \approx 5 \cdot 10^{-5}$ per channel. The partial yttrium spectra were corrected for gain shifts before being added. Fig. 4 shows examples of normalized linear spectra at various neutron energies. The spectra in b) and c) are averaged over three channels.

3. THE DSD MODEL

The inclusion of semi-direct mechanisms in radiative nucleon capture was proposed by several authors [Br65], [Lu65], [Cl65] after it became clear that the compound-nucleus and direct-capture processes alone failed to describe the experimental data in the GDR region.

In the early DSD model formulations the particle-vibration coupling consisted only of a real part. The predicted capture cross sections were in rough agreement with experimental data but did not reproduce the symmetric shape of the excitation functions in the region of the GDR. With a complex particle-vibration coupling [Sat72], good agreement was found between DSD calculations [Po73] and data for the reaction $^{208}\text{Pb}(n,\gamma)^{209}\text{Pb}$ in the neutron energy region 7-15 MeV [Ber72]. Recent developments of the model consist of adding resonant

quadrupole and octupole capture [Sap78], [Li79].

Here we confine the presentation to those equations which are essential for the discussion of the model parameters used in the calculations. The formulae are given for neutron capture and electric multipole transitions of order $L \leq 2$. In the DSD capture-mechanism picture, the amplitude T_{dsd} for capture of a neutron is given by

$$T_{dsd} = T_d + T_{sd}$$

where T_d and T_{sd} in turn are proportional to the radial matrix elements

$$T_d \sim \langle \Psi_{n1j} | \sum_L d_L(r) | \chi^+ \rangle \quad (1)$$

and

$$T_{sd} \sim \langle \Psi_{n1j} | \sum_{L\tau} \frac{h_{L\tau}(r)}{E_\gamma - E_{L\tau} + i \frac{\Gamma_{L\tau}}{2}} | \chi^+ \rangle. \quad (2)$$

The T_d describe the direct process in which a neutron undergoes a radiative transition of multipolarity L between the continuum state $|\chi^+\rangle$ and the bound single-particle state $|\Psi_{n1j}\rangle$ without exciting the core. The operators $d_L(r)$ are the effective charges. For a neutron these are given by

$$d_L(r) = - \frac{eZ}{(A+1)^L} r^L \quad (3)$$

where Z and A denote the charge and mass numbers of the target nucleus, respectively. In the semi-direct process the neutron is inelastically scattered into a single-particle state and the core excited to the collective state of multipolarity L before decaying to the state $|\Psi_{n1j}\rangle$ with emission of a γ ray. In eq. (2) $\tau=0$ and $\tau=1$ stand for isoscalar and isovector excitations, respectively. The $E_{L\tau}$ are the resonance energies

and the $\Gamma_{L\tau}$ the corresponding widths. The particle-vibration coupling is represented by the operators $h_{L\tau}(r)$ where

$$h_{L1}(r) \sim S_{L1} r^L [V_1 f_r(r) - iW_1 4b \frac{df_i(r)}{dr}] \quad (4)$$

and

$$h_{20}(r) \sim S_{20} r [V_0 \frac{df_r(r)}{dr} + iW_0 4b \frac{d^2 f_i(r)}{dr^2}]. \quad (5)$$

In eq. (4) V_1 and W_1 are the real and imaginary parts of the symmetry potential, respectively. V_0 and W_0 in eq. (5) are the real and imaginary parts of the central potential. The functions $f(r)$ are Woods-Saxon form factors. The $S_{L\tau}$ stand for the fraction of the energy-weighted sum rule (EWSR) exhausted by the resonances. In neutron capture only the $T_<$ component of an isovector resonance can be excited. For the GDR the fraction of the EWSR, $S_{1<}$, is given by [Fa70]

$$S_{1<} = \frac{T_0}{T_0 + 1} (1 + 1.5A^{-2/3}) S \quad (6)$$

where S is the total EWSR and T_0 is the ground-state isospin of the residual nucleus. For the IVGQR the $S_{2<}$ can be estimated using a similar expression [Kr84]

$$S_{2<} = \frac{T_0}{T_0 + 1} (1 + 2A^{-1}) S. \quad (7)$$

For ^{90}Y ($T_0=6$) eq. (7) gives $S_{2<}=0.88 \cdot S$

The continuum-state wave function, $|\chi^+\rangle$, was calculated using available optical potential parameters. We tested the sensitivity of the calculations to several parameter sets [Be69], [Ra79], [Wa85] and to parameters obtained recently for

yttrium in a neutron scattering experiment at $E_n = 21.6$ MeV [0185]. In the calculations we adopted the parameters of ref. [0185] together with the dependence of the parameters on energy given by ref. [Be69]. All the parameter sets provided fits to GDR data [Ber78] well within the experimental uncertainties. Applied to the present asymmetry data, all sets of parameters gave nearly the same results up to $E_n = 23$ MeV. Above 23 MeV, the parameters of references [Be69] and [Ra79] resulted in a steeper decrease in the A_1 values than those of references [Wa85] and [0185].

The single-particle wave functions were calculated with a shell-model potential whose depth was allowed to vary until the experimental binding energies of the states were reproduced. The calculations were carried out for the bound states listed in table I where the spectroscopic factors were taken from ref. [Go72]. The binding energies correspond to the centroids of the doublets in ^{90}Y . (see also [Ber78]).

Table I - Binding energies, E_b , and spectroscopic factors, SF, for the single-particle states of ^{90}Y included in the calculations.

nlj	E_b (MeV)	SF
$2d_{5/2}$	6.76	1.00
$3s_{1/2}$	5.57	1.00
$1h_{11/2}$	4.75	0.35
$2d_{3/2}$	4.31	0.75
$1g_{7/2}$	3.87	0.60

Although the direct E2 component is small it was included in the calculations in addition to direct E1 capture. The parameters used for the GDR were $E_{11}=16.7$ MeV, $\Gamma_{11}=4.1$ MeV, and $S_{11}=94\%$ of the total EWSR. For the ISGQR the parameters were $E_{20}=14.1$ MeV, $\Gamma_{20}=4.0$ MeV and $S=50\%$ of the isoscalar quadrupole EWSR. The values of V_0 and W_0 for the ISGQR were 50 and 5 MeV, respectively. The real part of the symmetry potential was $V_1=120$ MeV while the imaginary part, W_1 , was varied in the calculations. The parameters of Woods-Saxon form factors were the same for all the resonances. A radius $r_0=1.25$ fm was used in both the real and imaginary parts. The diffuseness parameters were $a=0.65$ fm and $b=0.70$ fm for the real and imaginary parts, respectively.

4. DATA ANALYSIS AND CORRECTIONS

The asymmetry values A_1 and A_2 are defined by equations 8 and 9, respectively:

$$A_1(\theta, E) = \frac{I(\theta, E) - I(\pi - \theta, E)}{I(\theta, E) + I(\pi - \theta, E)} \quad (8)$$

$$A_2(\theta, E) = 2 - \frac{4I(\pi/2, E)}{I(\theta, E) + I(\pi - \theta, E)} \quad (9)$$

where $I(\theta, E)$ is the yield at angle θ and energy E . In the case considered here, $L \leq 2$, the yields $I(\theta, E)$ are proportional to the Legendre polynomial expansion

$$I(\theta, E) \sim 1 + \sum_{i=1}^4 a_i(E) P_i(\cos \theta).$$

For $\theta=55^\circ$, the A_1 and A_2 values are related to the $a_i(E)$ coefficients through the formulae

$$A_1(55^\circ, E) = \frac{.0574a_1(E) - 0.389a_3(E)}{1 - 0.007a_2(E) - 0.385a_4(E)} \quad (10)$$

and

$$A_2(55^\circ, E) = 2 - \frac{2 - a_2(E) + 0.750a_4(E)}{1 - 0.007a_2(E) - 0.385a_4(E)} \quad (11)$$

From eq. (10) we note that non-zero A_1 values are due to the effect of interference between radiation of opposite parity. In the energy regions where $a_4(E)$ can be neglected, A_1 depends, to a good approximation, on odd Legendre polynomial coefficients only and eq. (11) becomes $A_2 \approx a_2$.

In the DSD calculations of A_1 and A_2 the $2d_{5/2}$ and $3s_{1/2}$ doublets of ^{90}Y were treated as single peaks (see table I). For the states at excitation energies between 2.1 and 2.9 MeV the final A_1 and A_2 were computed as weighted mean values of those for the $1h_{11/2}$, $2d_{3/2}$ and $1g_{7/2}$ states.

Except for the two lowest neutron energies the γ -ray yields were low. For the $2d_{5/2}$ ground state and the states above $E_x = 2.1$ MeV, the data were extracted as the channel contents in the corresponding energy regions, rather than applying the response function of the detector. The procedure is correct for the ground-state yield and, in view of the low intensity of the $2d_{5/2}$ and the $3s_{1/2}$ states, we considered it also justified in extracting the data for the $1h_{11/2}$, $2d_{3/2}$ and $1g_{7/2}$ states. The $3s_{1/2}$ yield, however, is strongly affected by the tail of the $2d_{5/2}$ ground state and by the high-energy side of the $2d_{3/2}$ states immediately below it in the spectrum. We tried to estimate and subtract this background but the results for the $3s_{1/2}$ state, shown in the next section, reflect undoubtedly the difficulties encountered in this procedure. At the neutron energies 11.8 and 13.7 MeV the tails from higher γ -ray energies were subtracted from the yield for the $1h_{11/2}$, $2d_{3/2}$ and $1g_{7/2}$ states.

The net spectra were corrected for γ -ray and neutron attenuation taking into account the anisotropy of the neutron flux over the sample. The corrections were obtained with a computer code in which the sample volume can be divided into as many cells as desired. The code calculates, for each cell, the attenuation of the neutron flux through the sample on its path to that cell and the attenuation of the γ -ray flux through the sample on its path from the cell towards the spectrometer. Total cross sections were considered in the calculations of γ -ray attenuation coefficients [St70]. The non-elastic neutron cross-section data are scarce for neutron energies above 10 MeV [BNL66]. However, concerning the asymmetry values, the important quantities are the quotients between the transmission coefficients at the different angles. The neutron-attenuation coefficients were calculated using the non-elastic cross sections. Using the total neutron cross sections which are a factor of two larger changed the correction for the yield at 55° relative to that at 125° , on the average, from 1.08 to 1.10.

The reaction angle distribution, caused by the size of the sample, had a slightly asymmetric shape with a width of about 19° (FWHM). This shifted the geometrical angle of the γ -ray spectrometer from 55° , 90° and 125° to the effective angles of 57.0° , 91.6° and 125.7° , respectively. The corrections to A_1 and A_2 for the angular spread, calculated with a Monte-Carlo method, were found to be negligible. The dead-time corrections, mainly due to the rejection of pile-up events, were the same (within 1%) for all angles at the same neutron energy.

5. RESULTS AND DISCUSSION

The analysis of the $2d_{5/2}$ ground-state data is straightforward. Although the statistics are poor, the uncertainties in the A_1 values are relatively small for the highest neutron energies due to the large ratio, about 10, between the yields at 55° and 125° . The A_2 values at $E_n = 11.8$ and 13.7 MeV show good agreement with the DSD predictions. It is however

unfortunate that the A_2 could not be measured more accurately for the higher neutron energies. On the one hand the DSD model predicts, for the $2d_{5/2}$ state (and also for the $3s_{1/2}$), a strong dependence of A_2 on the fraction of the EWSR exhausted by the resonance. On the other hand the experimental A_1 rise to large values where the model predictions, necessarily, become almost insensitive to variations in the resonance strength.

The A_1 and A_2 results for the $2d_{5/2}$ state are shown in figs. 5-7 where the data are successively compared with DSD calculations for different values of the strength, the imaginary part of the symmetry potential and the resonance width. Throughout the calculations the resonance was located at an excitation energy of 26 MeV.

For the calculations in figs. 5 and 6 we assumed a resonance width $\Gamma=9$ MeV. The depth of the imaginary part of the symmetry potential was $W_1=80$ MeV in the calculations shown in figs. 5 and 7. Together with a depth $V_1=120$ MeV for the real part of the symmetry potential, this value of W_1 provides the best fit to the cross-section data in the GDR region [Ber78]. The best values of $S_{\leq}$ and W_1 , namely $S_{\leq}=150\%$ of the EWSR and $W_1=80$ MeV, from figs. 5 and 6 were used in the calculations shown in fig. 7 which were performed for different widths. From fig. 5 we deduce that, irrespective of the other parameters used in the calculations, a large strength is needed to describe the data. In our approach none of the parameters can be extracted independently of the model calculations. We note however from fig. 6 that the variation in W_1 does not alter the maximum of A_1 but only changes its position along the energy axis. A change of W_1 from 50 to 100 MeV changes the apparent location of the resonance by less than 2 MeV. We conclude, based on the best value of W_1 for the GDR region, that the resonance is located at 26 ± 1 MeV. The calculations in fig. 7 show that the asymmetry values are not sensitive to changes in the resonance width. Although the data are best described by a width $\Gamma=11$ MeV, the lower values can not be excluded.

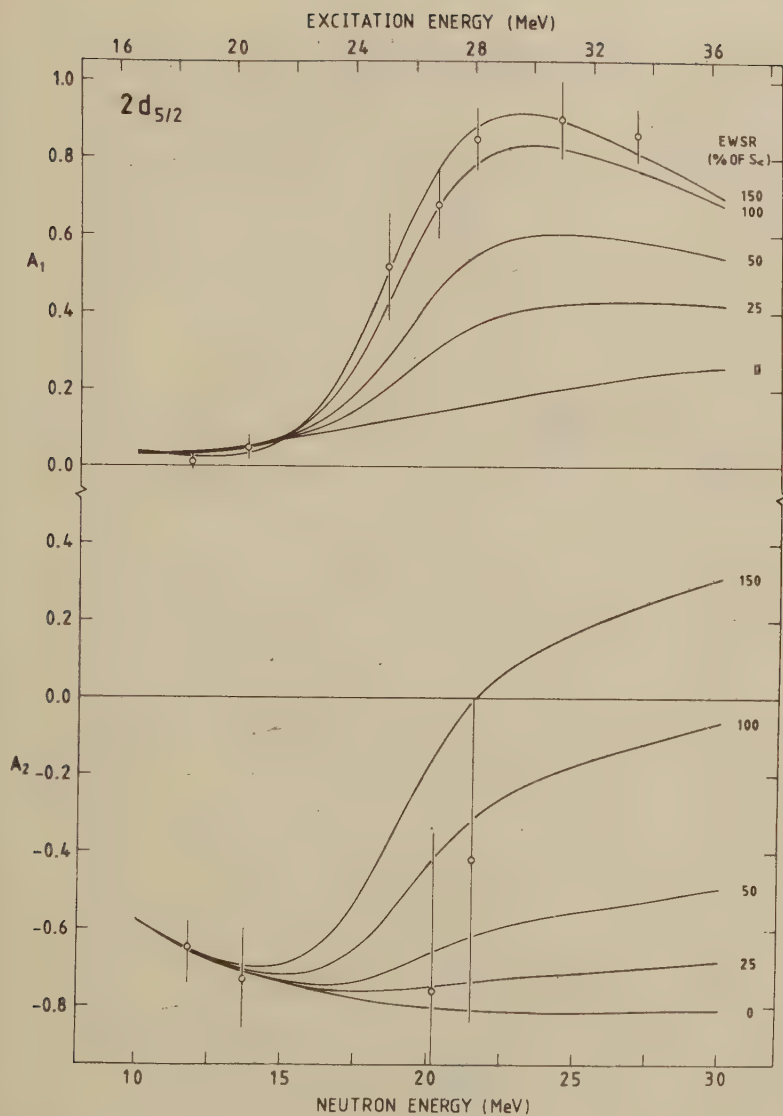


Fig. 5- A_1 and A_2 values for transitions to the $2d_{5/2}$ ground state of ^{90}Y . The curves are the results of DSD calculations for isovector E2 strengths shown to the right. The resonance is located at an excitation energy of 26 MeV. The resonance width is $\Gamma=9$ MeV and the imaginary part of the symmetry potential is $W_1=80$ MeV.

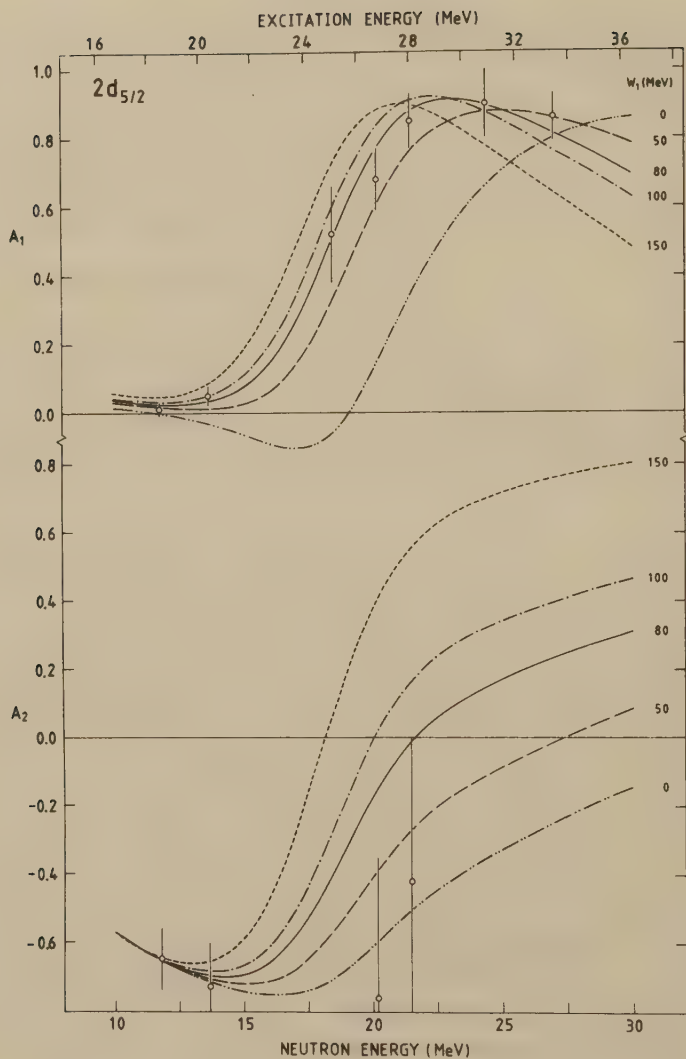


Fig. 6- See caption to fig. 5. In this figure, the imaginary part of the symmetry potential, W_1 , is varied while the strength is $S_<=150\%$ of the $T_<$ EWSR and the width is $\Gamma=9$ MeV.

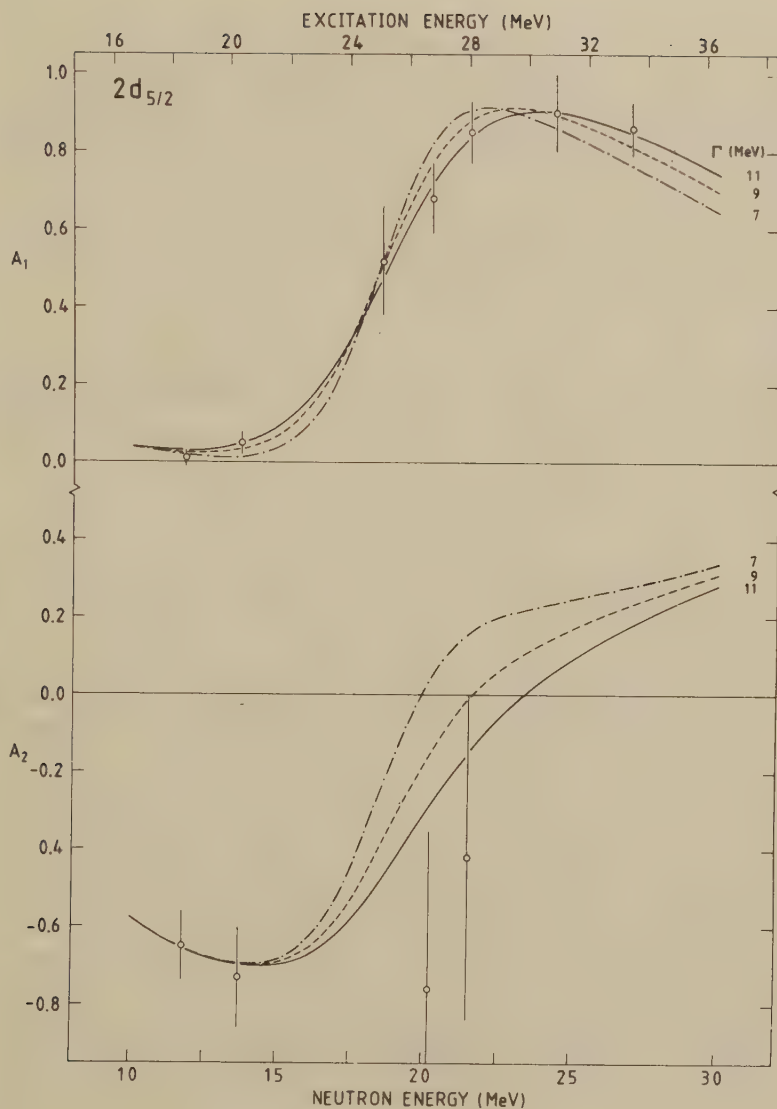


Fig. 7- See caption to fig. 5. In this figure, the resonance width, Γ , is varied while the strength is $S_{<}=150\%$ of the $T_{<}$ EWSR and the imaginary part of the symmetry potential is $W_1=80$ MeV.

In fig. 8 the experimental data for all the states are shown together with DSD calculations. For the $3s_{1/2}$ state the data are very uncertain for reasons outlined in the previous section. The data for the $1h_{11/2}$, $2d_{3/2}$ and $1g_{7/2}$ states have small statistical uncertainties if, as in the present work, these are considered as one entity. The spectroscopic factors obtained from neutron-transfer experiments [Go72] were used in the DSD calculations. These should nearly exhaust the single-particle strength in this energy region (see table I).

Since the multipolarity of the resonance can not be determined from our data, one may ask whether the observed asymmetry values are due, in total or partly, to the decay of the isovector giant quadrupole state. Apart from E2, it would be most plausible to assume the presence of E3 strength in this energy region. In fact, several experiments have revealed isoscalar octupole resonances at $E_x \approx 110A^{-1/3}$ i.e., slightly below the IVGQR. Non-zero A_1 values, however, rule out the possibility of E3 strength alone with E1. Although the isoscalar modes are weakly excited through neutron capture reactions, we performed DSD calculations which show that our A_1 data can not be explained by the presence of E3 strength. In addition to the amplitudes already considered, we included in a calculation an isoscalar and an isovector E3 resonance at $E_x = 14$ and 43 MeV respectively. Both resonances were assumed to exhaust 100% of the EWSR. In another calculation the IVGQR was substituted by an E3 isovector resonance having the parameters used in the calculations of fig. 8. We also performed calculations assuming a surface shape for the symmetry potential where the depths of the real and imaginary parts were set at $V_1 = 120$ MeV and $W_1 = 80$ MeV, respectively. This provided a poor description of the asymmetry data for the $2d_{5/2}$ state.

In conclusion, we attribute the large asymmetries observed to the effects of interference between γ rays from dipole transitions and γ rays from the isovector giant quadrupole

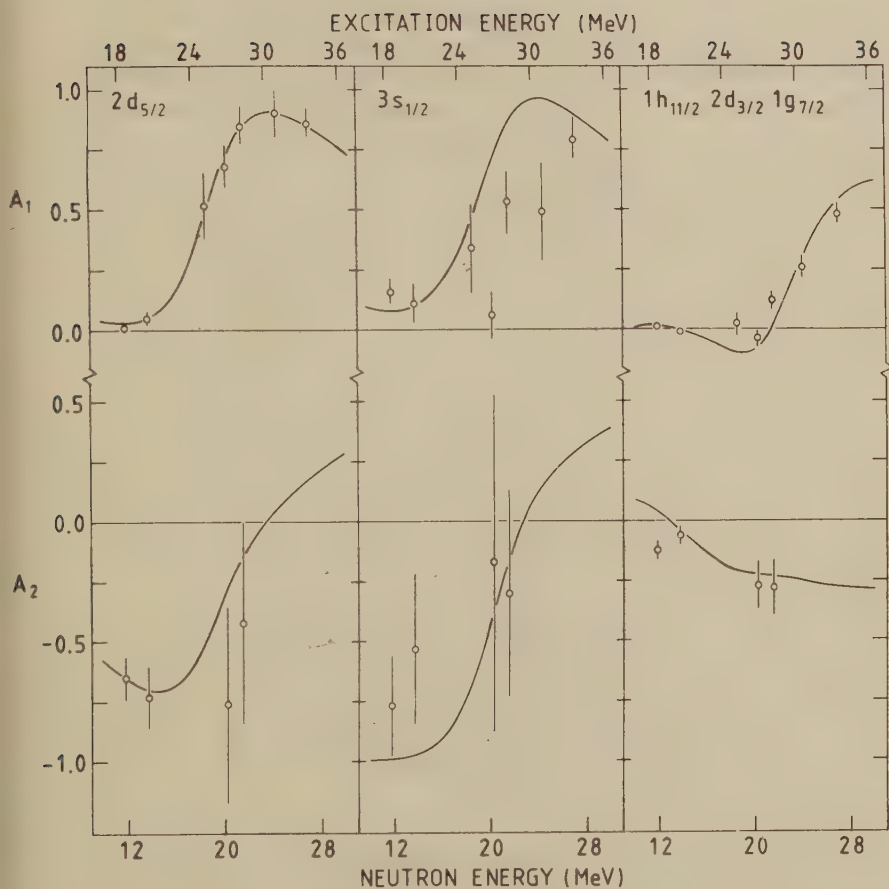


Fig. 8- A_1 and A_2 data for the different states together with DSD calculations. As in the previous figures, the resonance is located at 26 MeV. Here, the calculations were carried for $S_{\infty} \approx 150\%$ of T_{∞} EWSR, $\Gamma = 11$ MeV and $W_1 = 80$ MeV. The calculations for the $1h_{11/2}$, $2d_{3/2}$ and $1g_{7/2}$ states are weighted mean values of the individual states.

state. The present data show the same behaviour as observed in earlier neutron-capture experiments on ^{208}Pb [Dr81] and ^{40}Ca [Ber84] in the region of the IVGQR. Analysed in the framework of the DSD model, the data show that the isovector E2 resonance is located at 26 ± 1 MeV and has a width $\Gamma = 10 \pm 2$ MeV. These values are in good agreement with the results of inelastic electron scattering [Fu76] [Pi77] and proton-capture experiments on ^{89}Y [Di77]. The data are consistent with a strength equal to the sum rule for the T_{-} IVGQR. This is in contrast to the results from charge-exchange reactions [Er84], [Ta84].

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